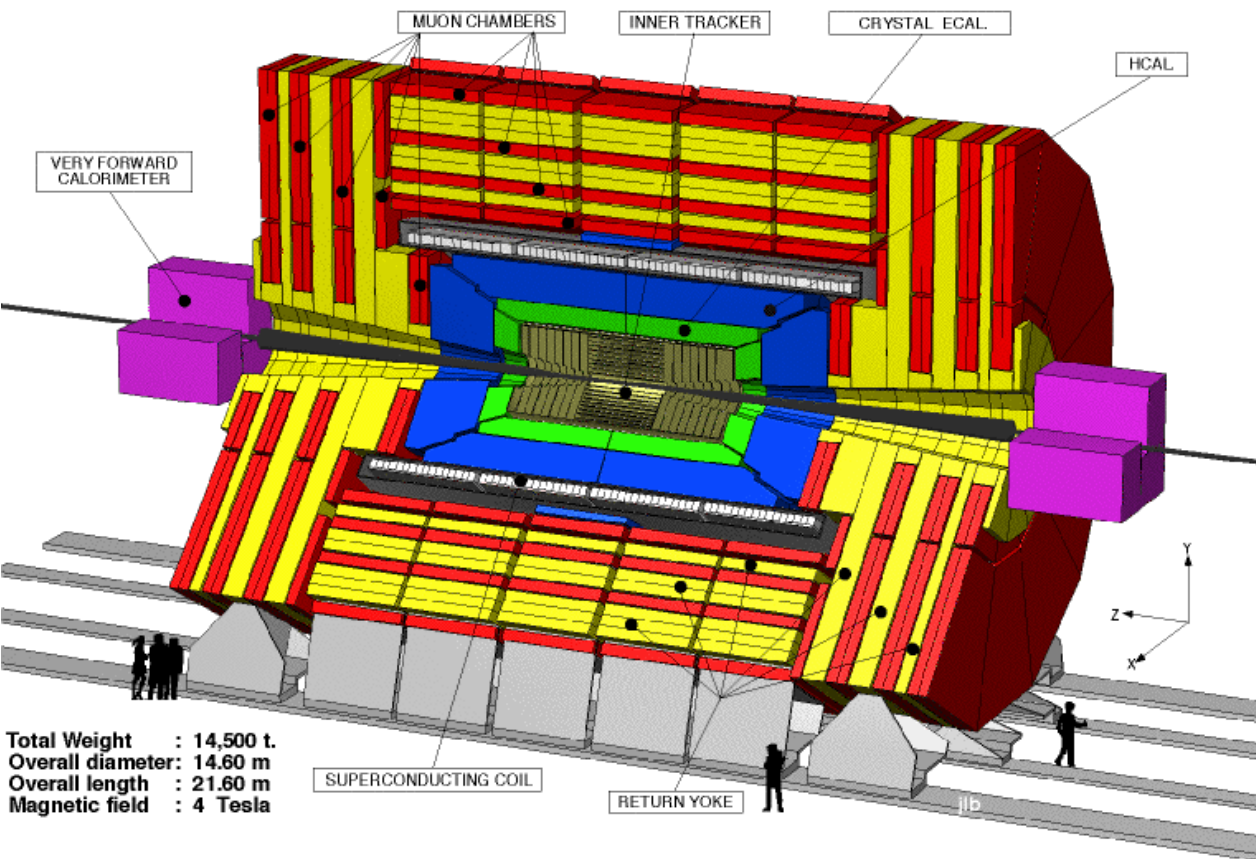


CMS Track Trigger: Tower definition and optimization

Olmo Cerri – September 22th 2016

Supervisor: Luciano Ristori

The Compact Muon Solenoid



Collaboration:

- 3500 scientist
- 43 countries

Location:

- Worldwide construction
- Now at LHC – IP8

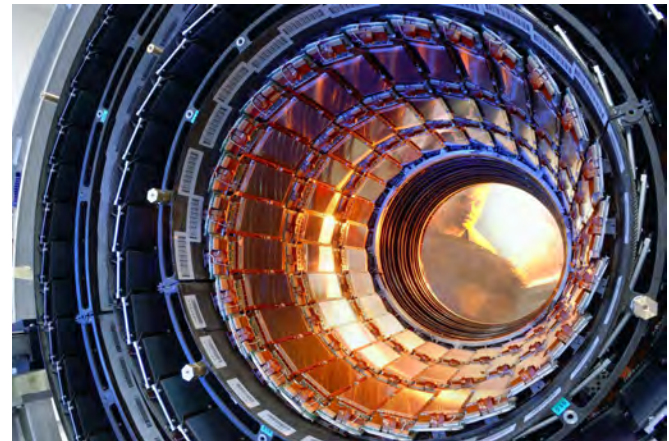
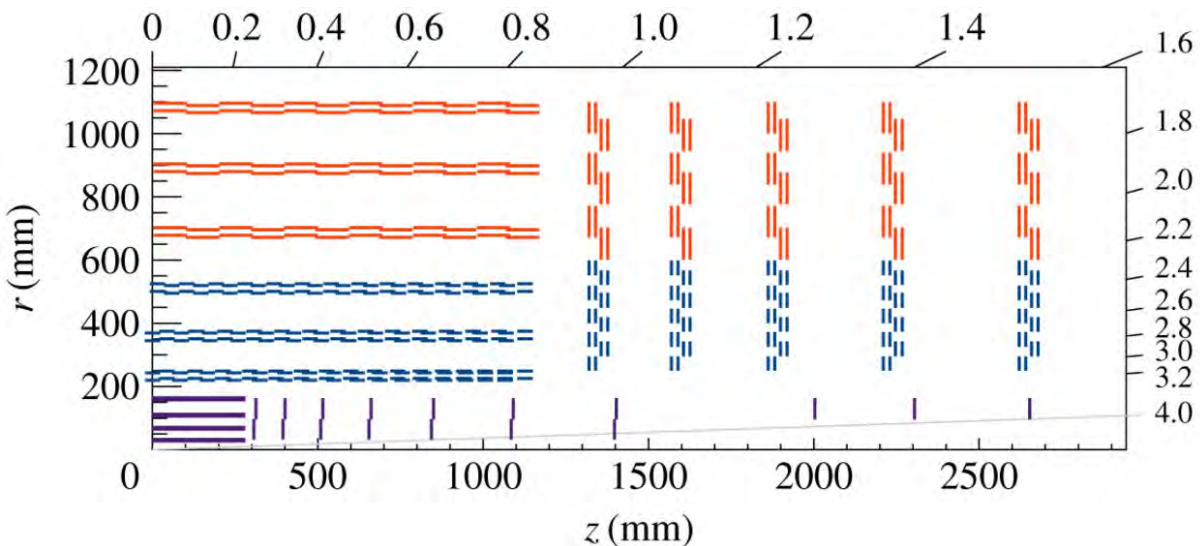
Strength:

- Hermeticity
- Precise measurement of charged tracks momenta
- Particle ID

General purpose experiment:

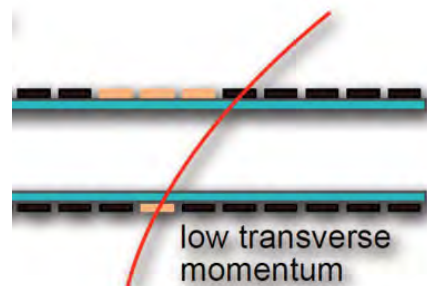
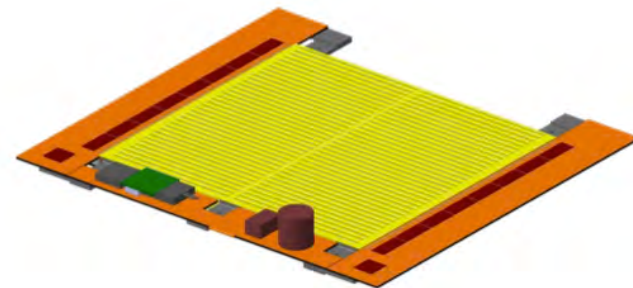
- Standard Model (Higgs, top...)
- New physics searches: (BSM, dark matter...)

CMS Tracker



Silicon strip:

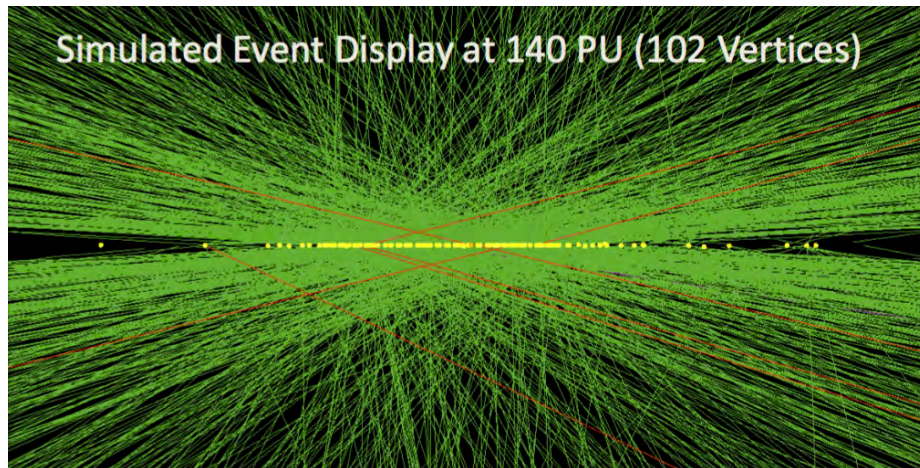
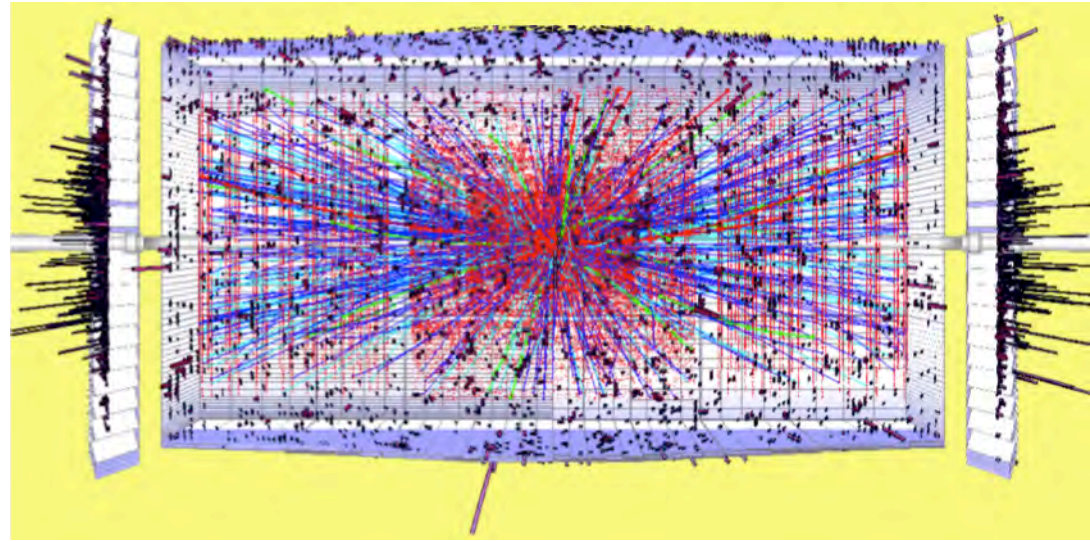
- 200 m² active area, 9.6 M channel
- 10x10 cm² modules
- Strip dimensions: 90μm x 5cm
- 2 strip sensors on top of each other : crude P_T threshold



The challenge: HL-LHC

Machine:

- Same tunnel as LHC
- Installation in 2023
- Physics run in 2026
- from 300 to 3000 fb⁻¹
- 25 nm bunch crossing
- $L_{\text{peak}} \geq 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



Each event:

- 14 TeV energy
- Up to 200 average simultaneous interactions
- 1000 Tb/s from silicon tracker

Trigger

All data can not be stored at that rate



Trigger: real-time event selection

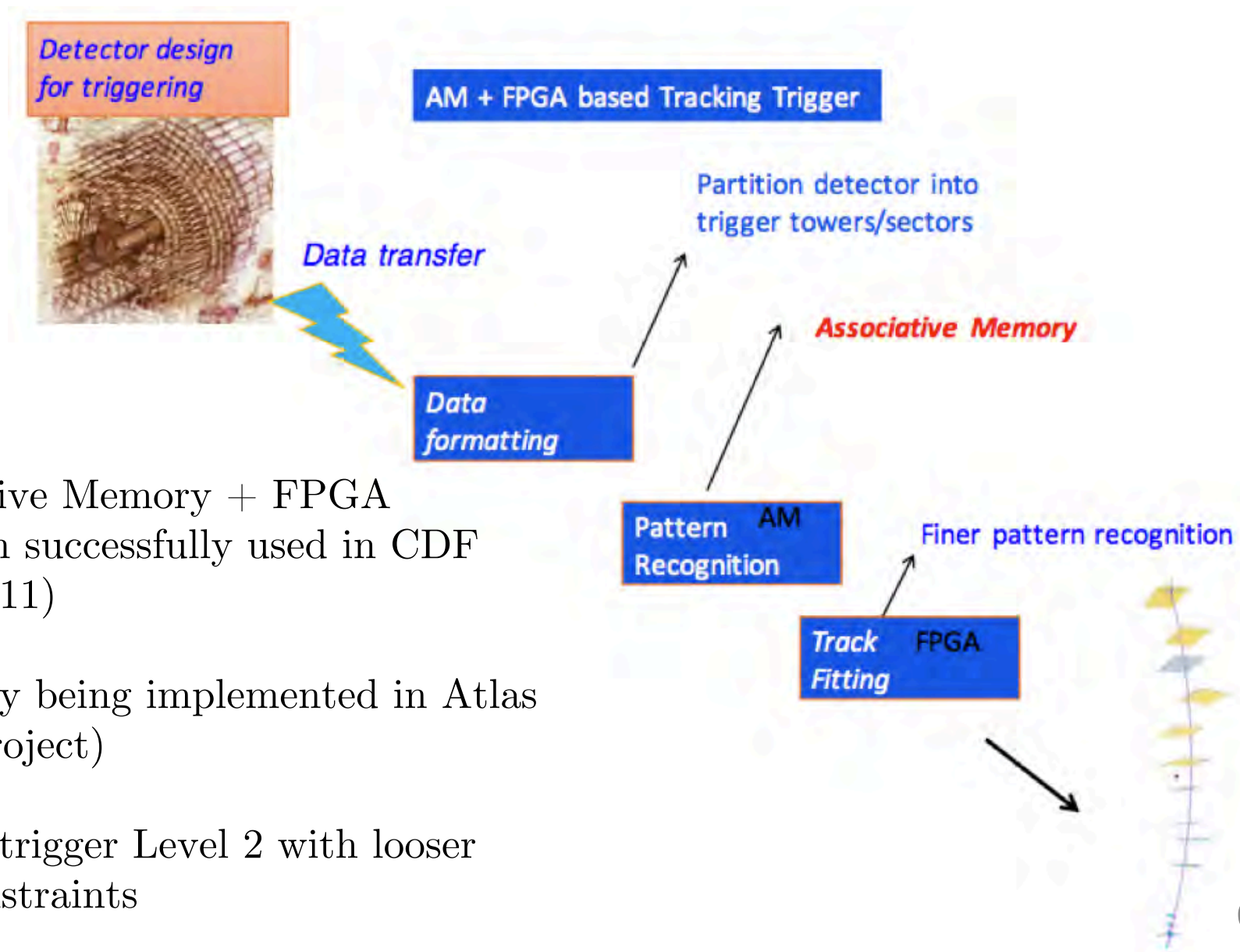
Phase II upgrade goal:

Implement tracks reconstruction in few μs for L1 trigger use

Extremely challenging goal:

- 40 MHz crossing frequency (one each 25 ns)
- $\sim 20,000$ hits/crossing
- ~ 100 tracks to be identified above $2\text{GeV}/c$ P_T
- Track parameters to be extracted with quasi-offline precision

AM + FPGA approach



- Associative Memory + FPGA approach successfully used in CDF (2002-2011)
- Currently being implemented in Atlas (FTK project)
- Both at trigger Level 2 with looser time constraints

Simulated example

Stubs

**Matched
roads**

Tracks

RAW

AM chips

FPGA

8240 stubs

**532 stubs and
proto track
candidates**

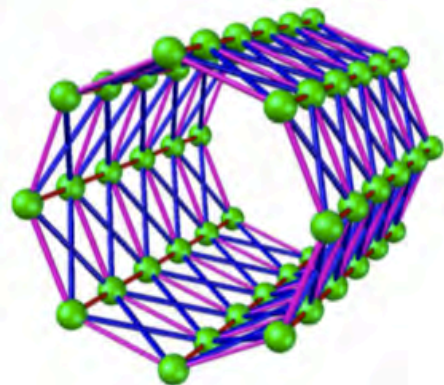
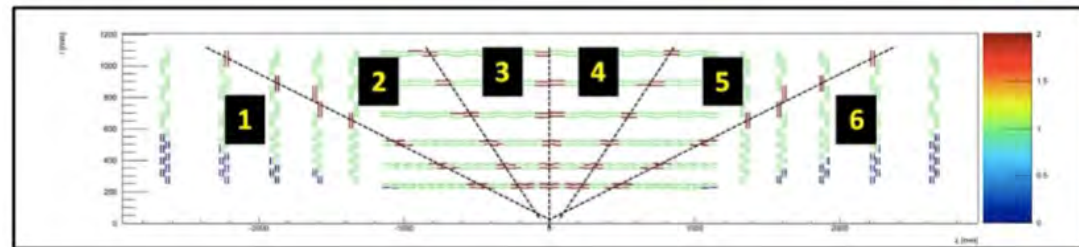
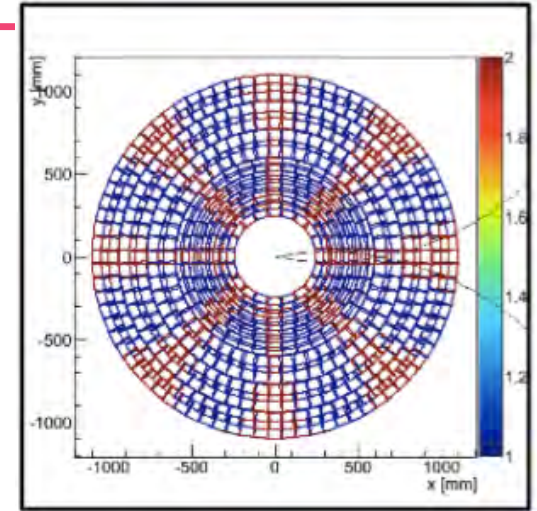
**281 stubs and
fitted tracks**

Balancing the workload:

AM Pattern Bank size VS FPGA resources/latency

Divide and conquer

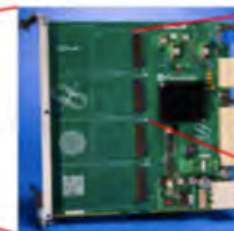
- Detector can be sliced into independent regions (Trigger Towers)
- Each one need its own electronics (ATCA crate)
 - Data collection from front-end modules
 - AM pattern recognition
 - FPGA for track fitting
- 8 region in ϕ and 6 in η
- = 48 towers



ATCA



ATCA crate



PULSAR IIb



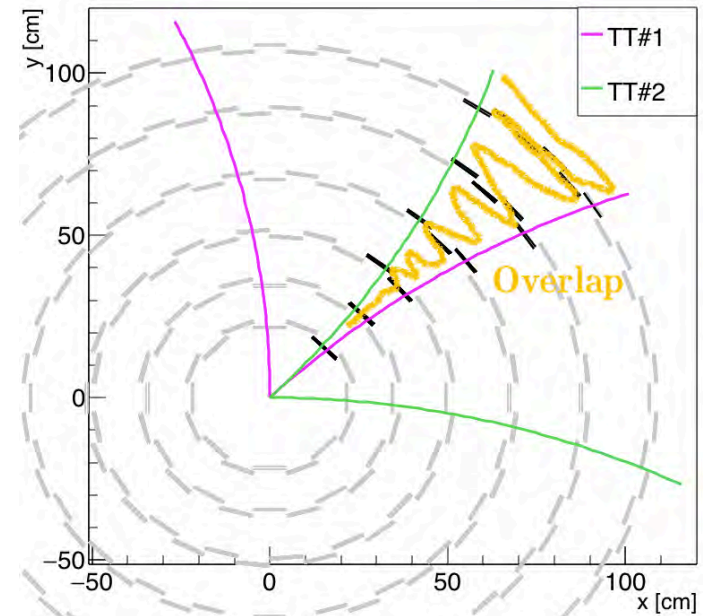
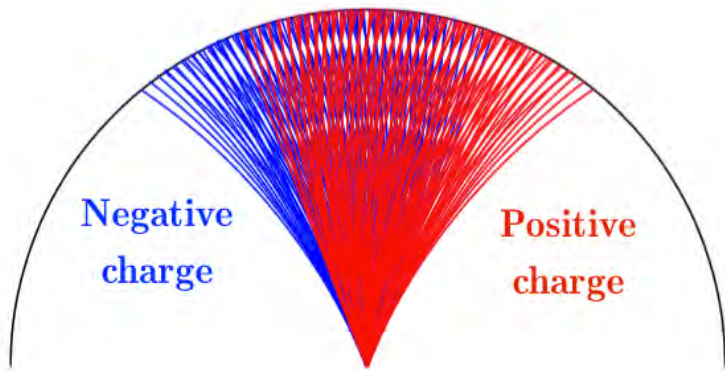
PRMs

TT definition procedure

- Divide parameter space into 48 non-overlapping regions
- Assign one tower to each region
- Define 48 “training samples”, one per tower
 - Use single muon sample
 - 2π in φ and $\eta = [-2.4, +2.4]$
 - $P_T \geq 2 \text{ GeV}$ and $\sigma_z = 5 \text{ cm}$
 - Select tracks from one of the 48 regions
- Assign modules to a tower
 - Go through the tracks in the corresponding training sample
 - Add all modules hit by at least one track

TT definition problem

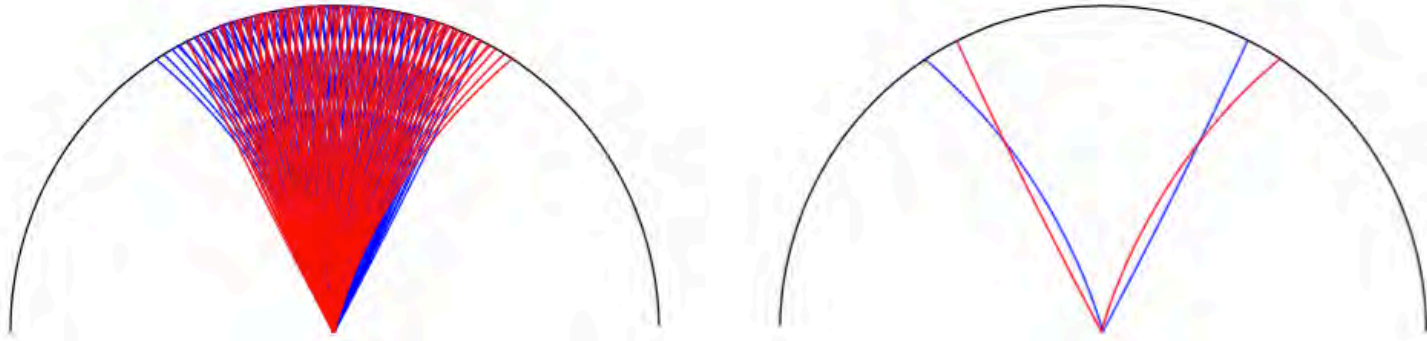
- Track parameter space is 4-dim (q/P_T , ϕ , η , v_z)
- 4-dim region can be conveniently defined by the intersection of two weakly correlated projections: (q/P_T , ϕ) and (η , v_z)
- Disjoint phase-space regions correspond to overlapping physical regions
- Overlap due to track curvature (ϕ) and to finite v_z dimension (η)



One of the goals is to minimize overlap regions without compromising acceptance

Minimizing the Overlap

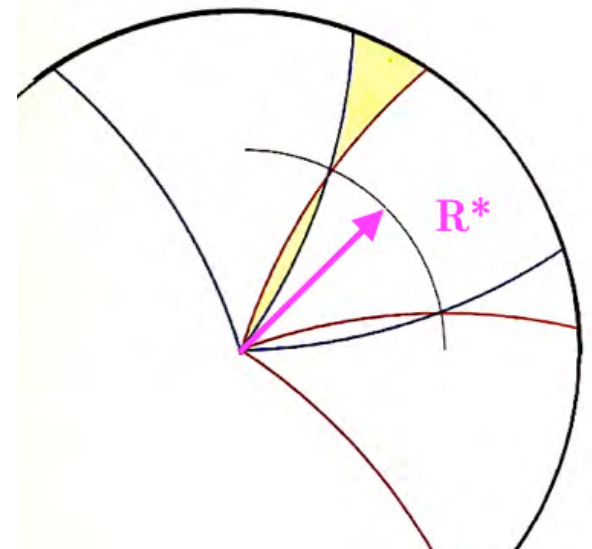
Shift **positive** wrt **negative** tracks:



Less overlap needed!

Regions are better defined in terms of $\phi(R^*)$ instead of $\phi(0)$

- Minimize the number of detector modules to be shared among trigger towers



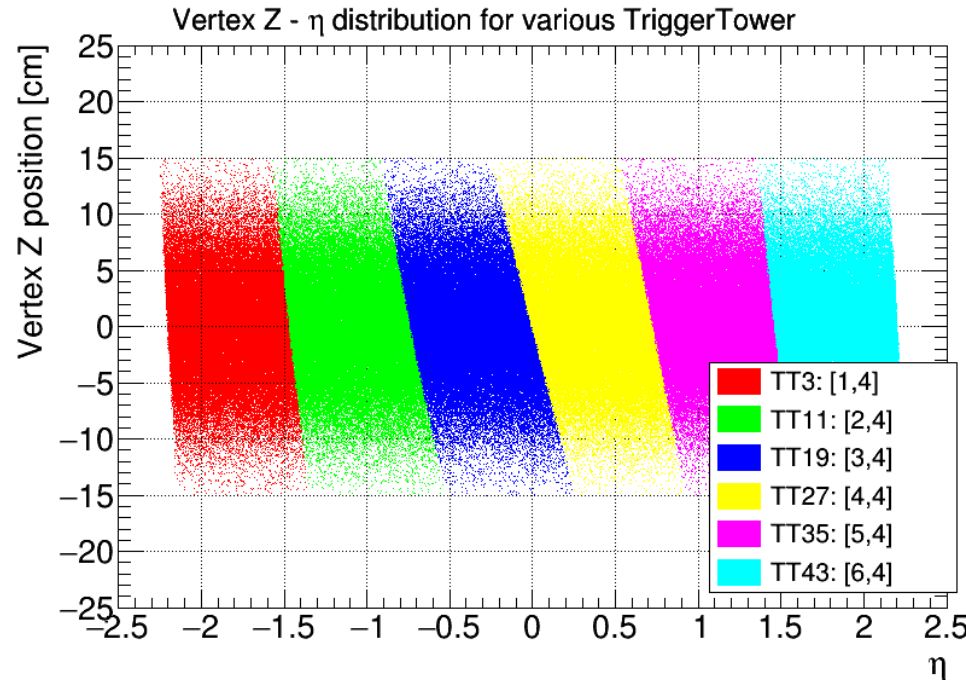
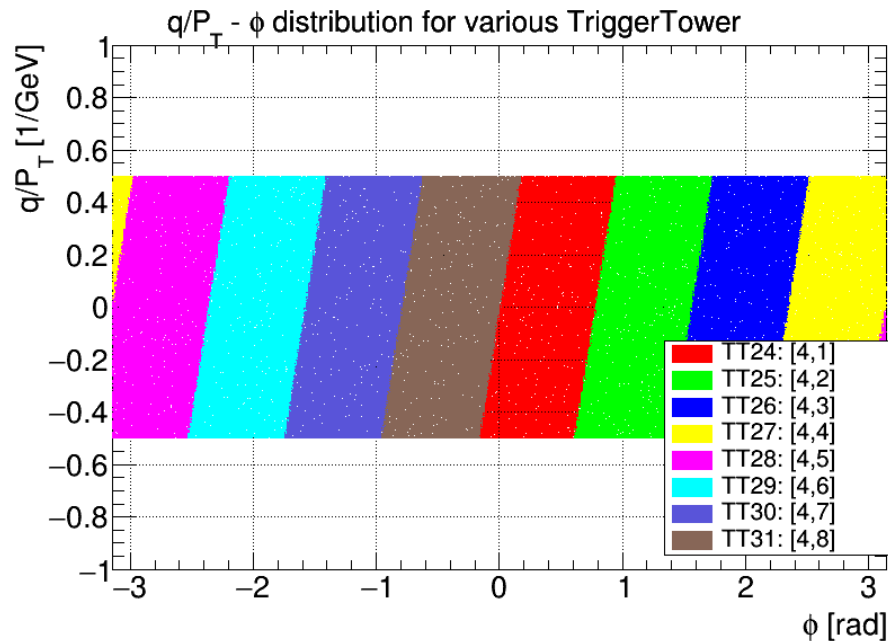
Parameter space regions

- Defined in terms of R^* :
 - $\eta^* = \eta(R^*)$
 - $\Phi^* = \Phi(R^*)$
- 8 equal division in Φ^*
- 6 equal division in η^*

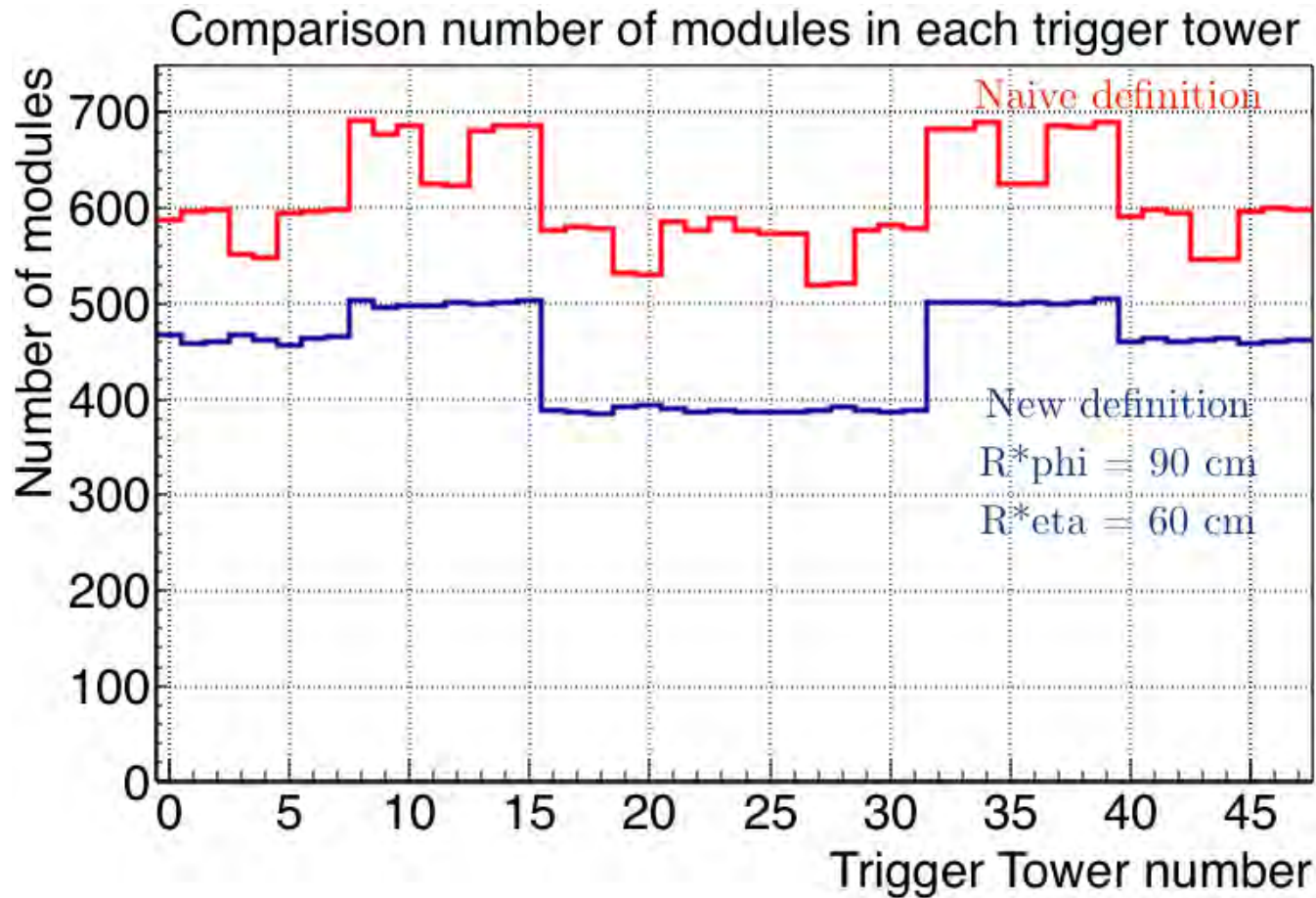
$$R_\phi^* = R_\eta^* = 58.89 \text{ cm}$$



Might be further optimized

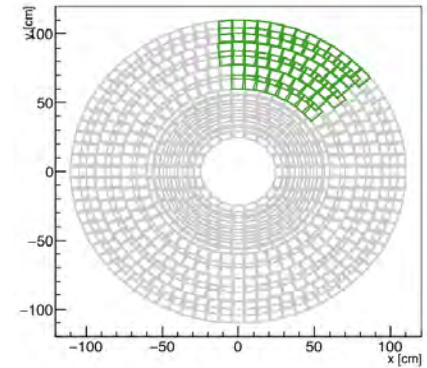
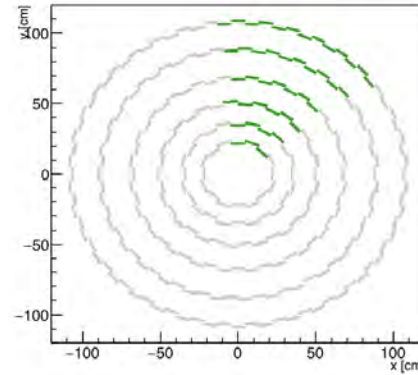
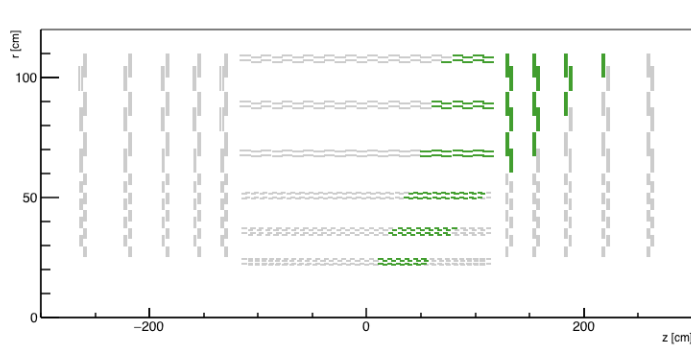


Naiïve vs New definition

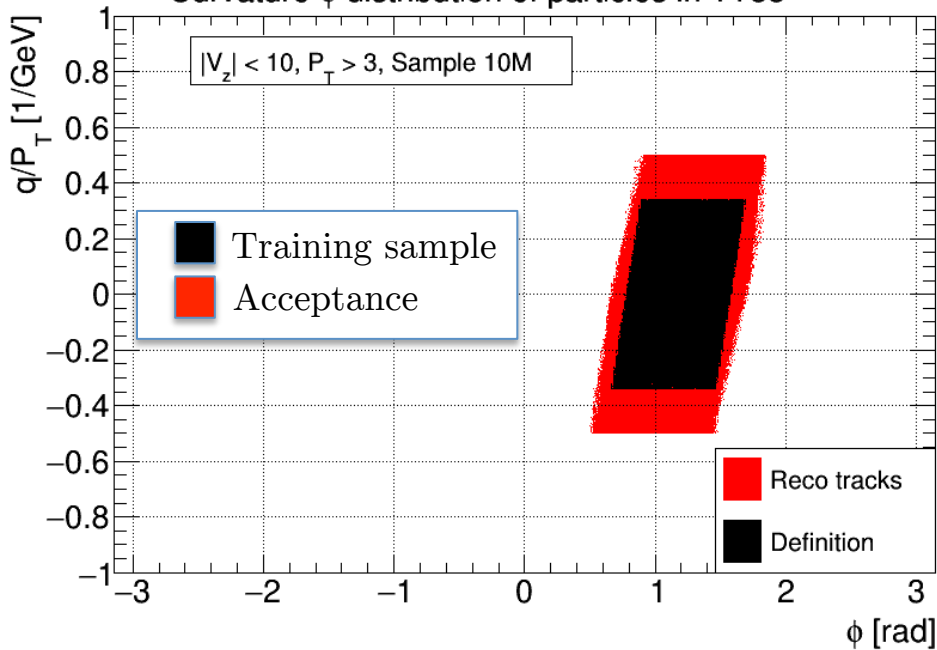


Each tower needs to see 400-500 front-end modules

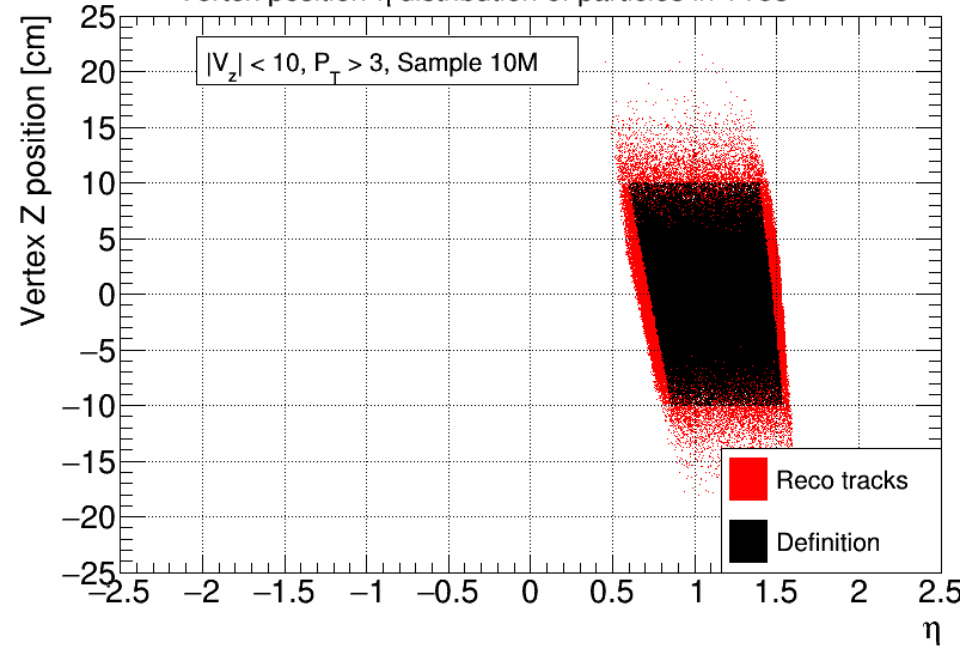
Intermediate example – TT[5,2]



Curvature- ϕ distribution of particles in TT33

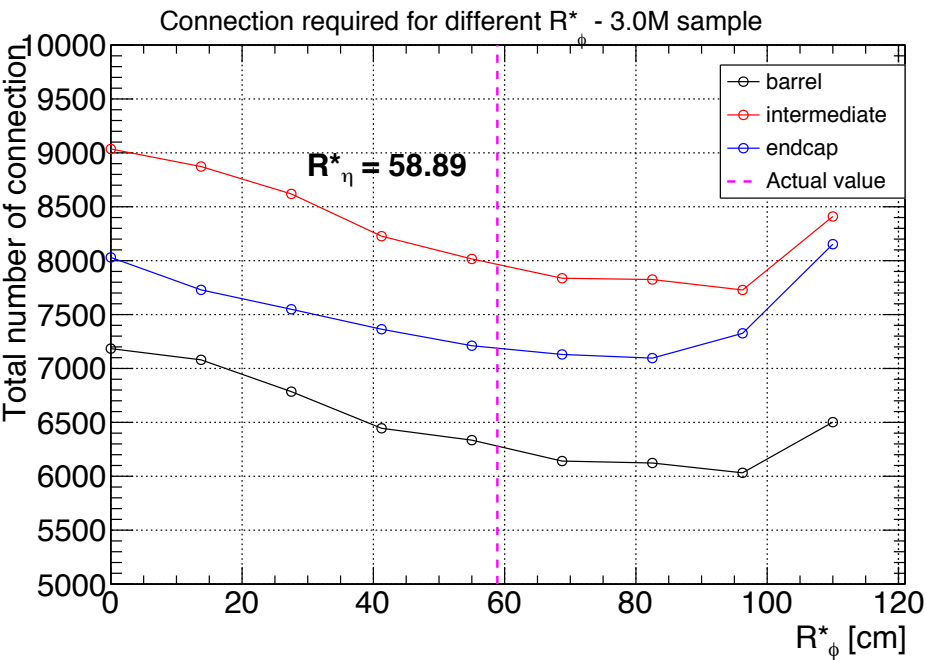


Vertex position- η distribution of particles in TT33

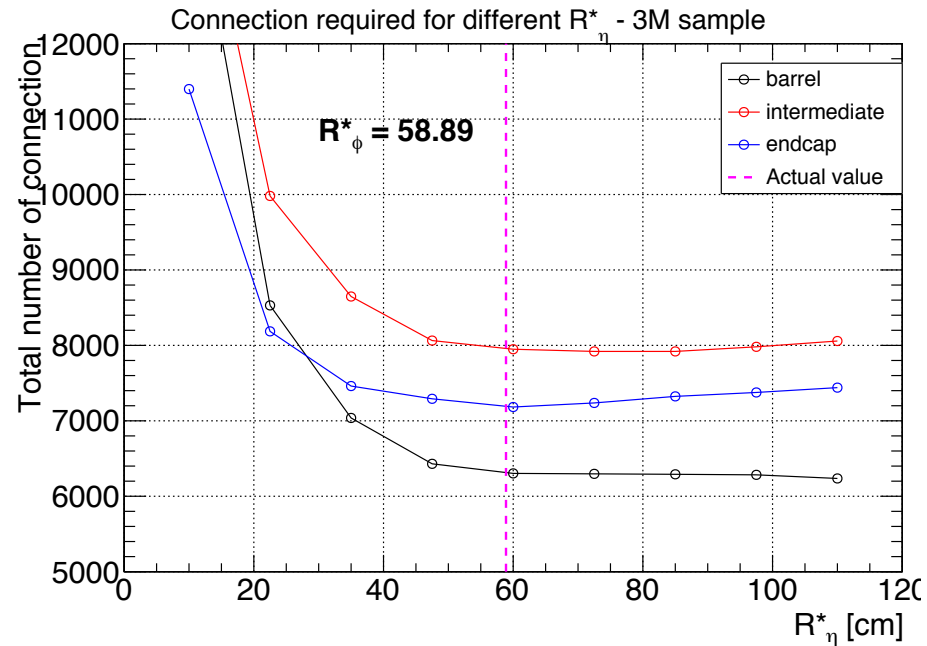


R^* optimization

- Optimization parameter: total number of connection between TT and modules
- Barrel, intermediate and forward regions treated separately
- Scan R^* in one view for a given R^* on the other



R^*_ϕ can be optimized up to 5%



R^*_η is already in a minimum plateau

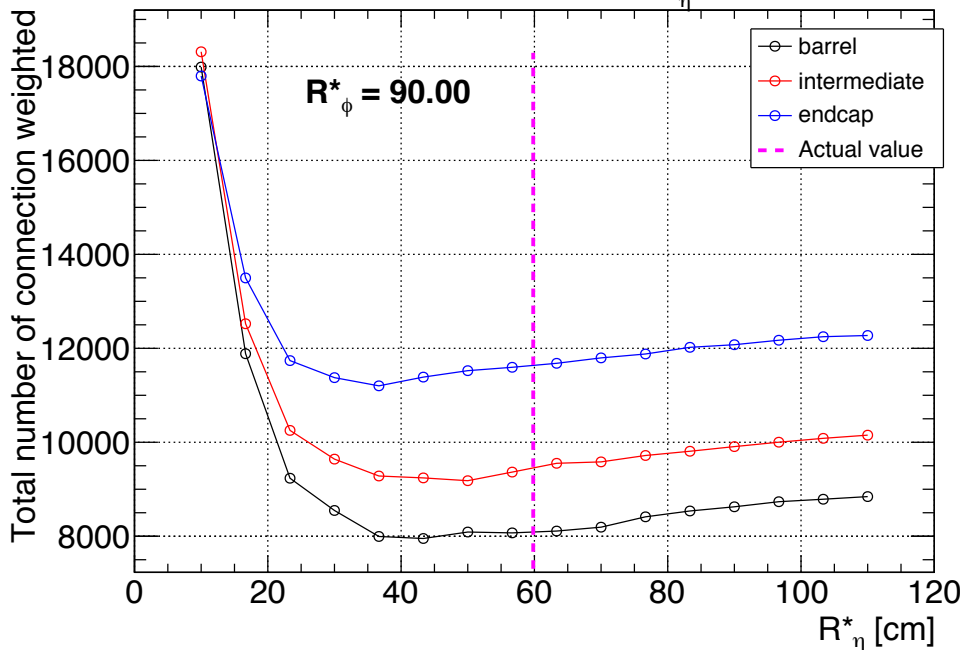
A different R^* optimization

- Number of modules R^* optimization:
 - Goal: Minimize the number modules connected
 - High R^*_{phi} are favored because of module dimensions
- First study does not take in account that same modules produce a significant larger number of stubs wtr to other ones
 - E.g. inner or forward modules are more likely to be overcrowded by pileup events
- New different study has been done to take in account this effect
 - Each module has to be weighted using the amount of stubs that produce on average
 - ✦ PU only events can be used to establish weights
 - Minimize the sum of the weights
 - Inner and forward modules are disfavored

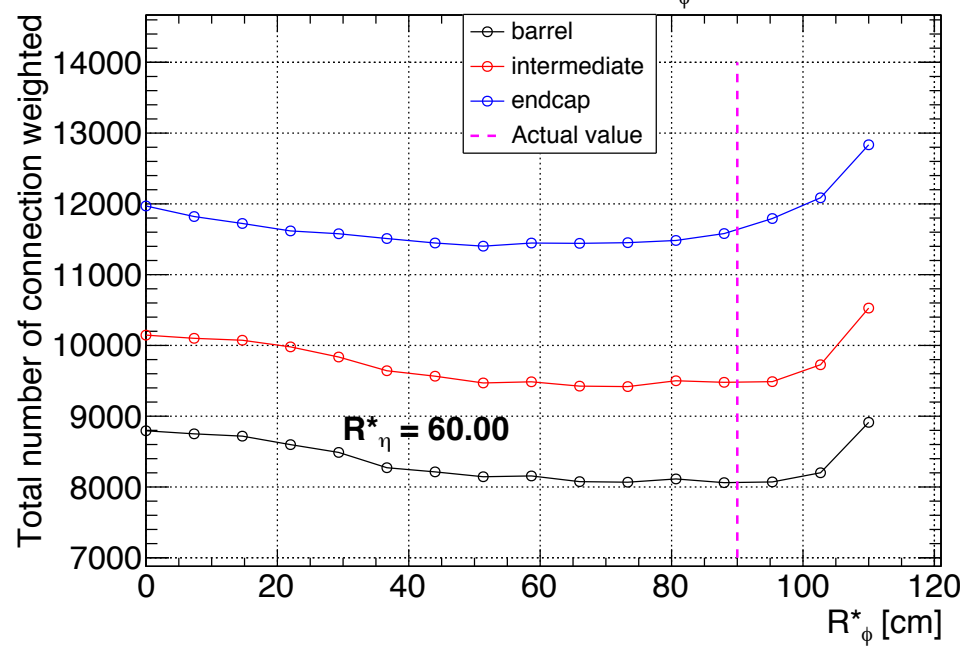
R^* weighted results

Actual values corresponds also
to previous study minimum

Weighted Connection required for different R^* - 5.0M sample



Weighted Connection required for different R^* - 5.0M sample



- To be compared with slide 15
- Different approach different results
- Minima seems slightly deeper and displaced to lower R^*
- To be understand what will be the real bottleneck and which optimization is more useful

Modules per tower - acceptance trade-off

Target:

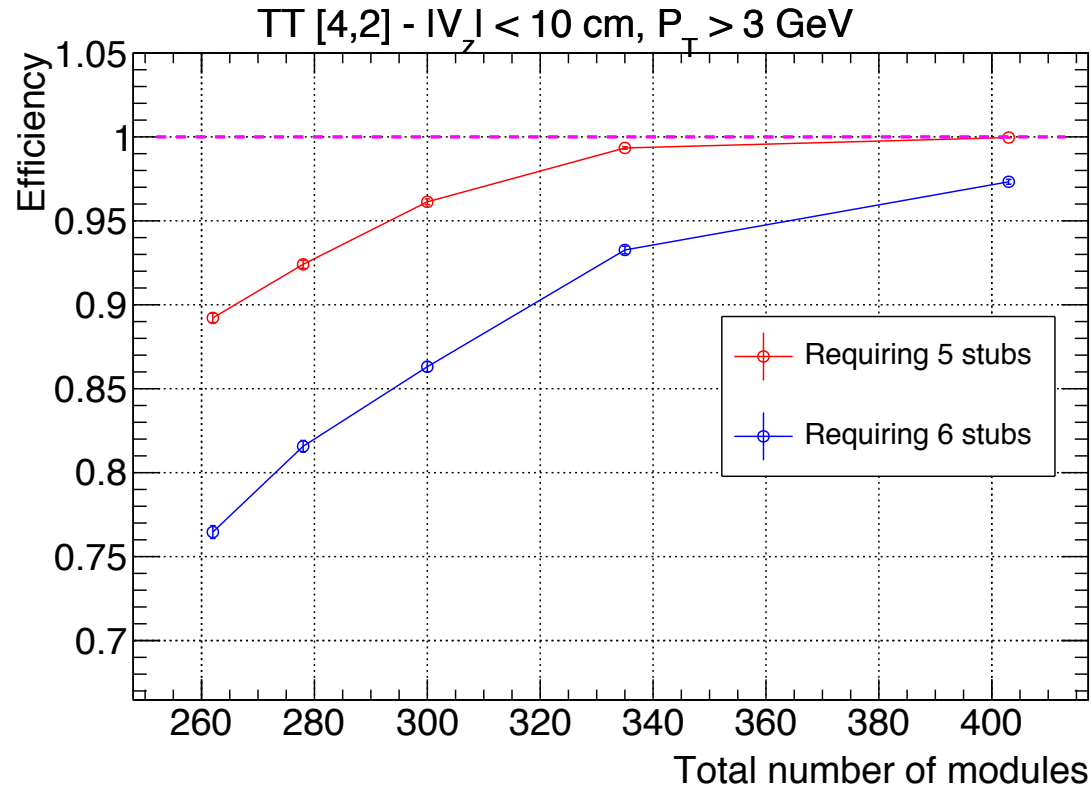
- Minimize the number of modules included in each tower:
 - Remove modules less involved
 - Compromise between acceptance and simplicity

Strategy:

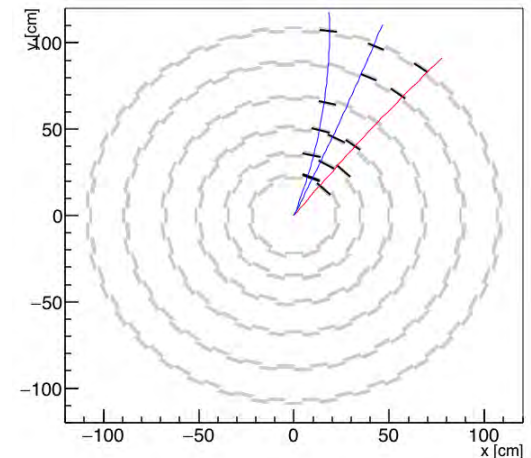
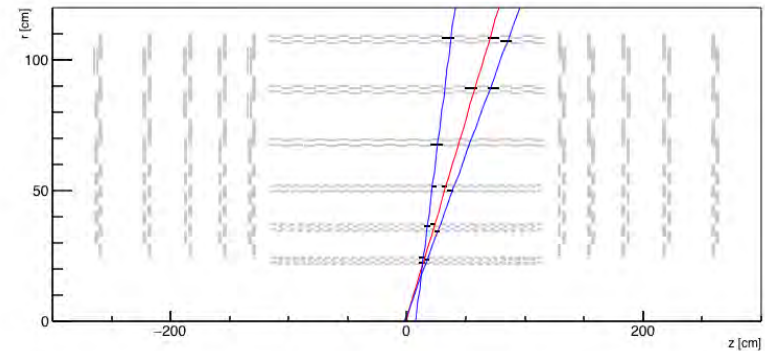
- Inclusive simulation: 4π muons shooting
- For each TT: counters of stubs detected in each module
 - Inside layer: modules sorting by the number of stubs detected
 - For each layer: include modules in TT list following the order and stop when the sum reaches a given threshold
- Compute efficiency:
 - Denominator: all tracks whose parameters fall inside the appropriate phase-space region
 - Numerator: tracks that have at least 5(6) stubs in modules belonging to the TT in 5(6) different layers

Efficiency: Barrel

Thr values = {1., 0.99, 0.97, 0.95, 0.93}



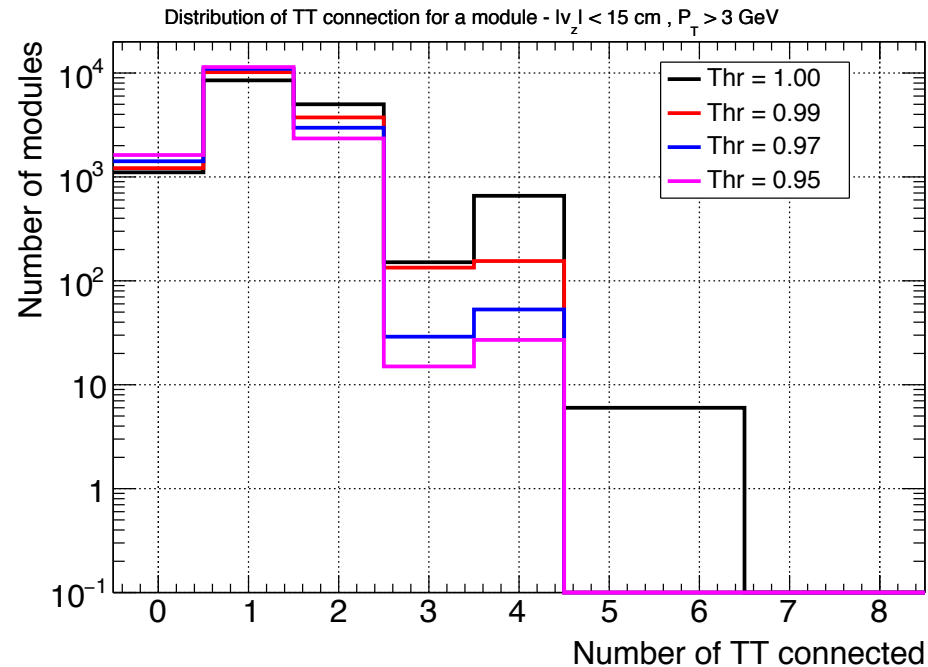
Example of inefficiencies:



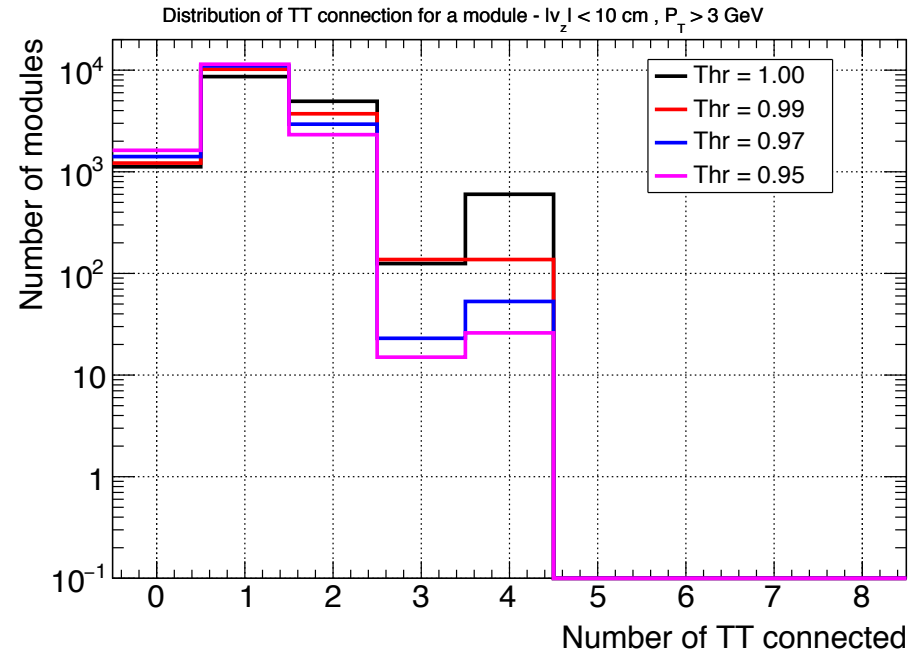
- With 17% less modules, efficiency drop by few percent

Connection per module – Threshold tradeoff

$$v_z = [-15 \text{ cm}, +15 \text{ cm}]$$



$$v_z = [-10 \text{ cm}, +10 \text{ cm}]$$



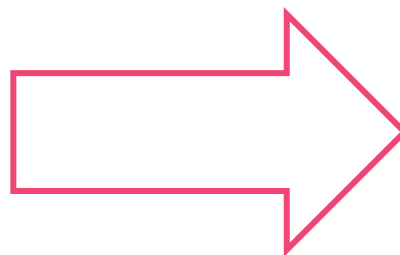
- The distribution remains essentially the same
- Multiple connection can be avoided paying some acceptance

From Parameters to CSV file

INPUT

- P_T threshold
- v_z acceptance
- R_{phi}^*
- R_{eta}^*
- Single Muon sample

FULL SIMULATION



OUTPUT

- TT modules list
- TT physical boundaries on each layer
- Whole detector
- Format: “.csv” file

Current setup:

- $P_T > 3 \text{ GeV}$
- $v_z = [-15 \text{ cm}, +15 \text{ cm}]$
 - $R_{\text{phi}}^* = 90 \text{ cm}$
 - $R_{\text{eta}}^* = 60 \text{ cm}$
- 20M Single Muon event (4π generation)

Tracking trigger simulation

- Only for TT25: [4,2] (Old TT27)
- Using current L1TT simulation code + modification (<https://github.com/ocerri/SLHCL1TrackTriggerSimulations>)
- Pattern bank generation
 - Raw sample of 1G single muon
 - Stub cleaning and sample shrinking
 - Pattern bank generation
- Performance check
 - New vs Old bank size comparison
 - Average number of roads in TTbar + PU140 events
 - Efficiency and resolution

Training sample generation

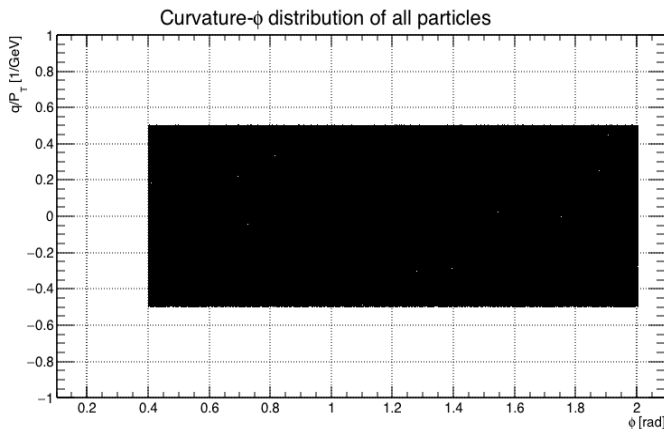
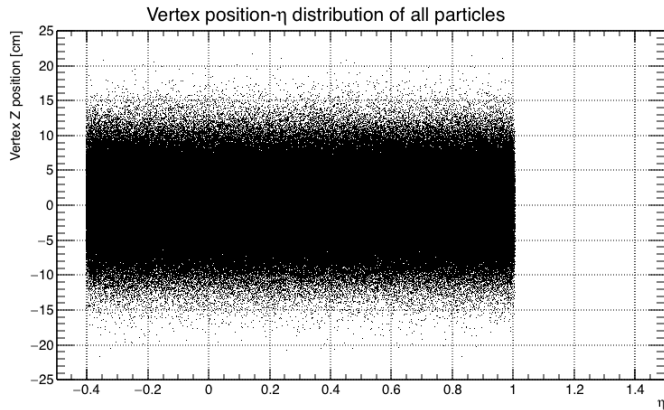
Raw sample:

- 800M single muon events
- Wider for future studies

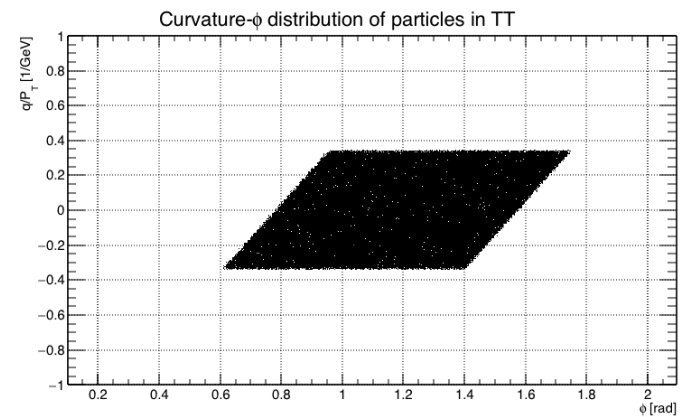
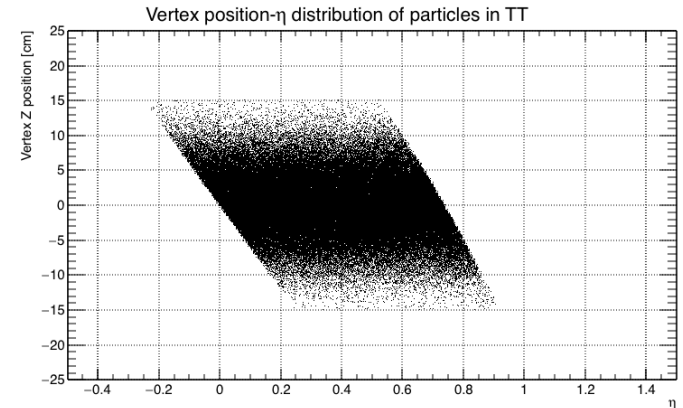
Stub Cleaner
&
Shrinking

PB training sample:

- About 134M muons
- Strict TT25 definition



StubCleaner.cc



Pattern bank generation

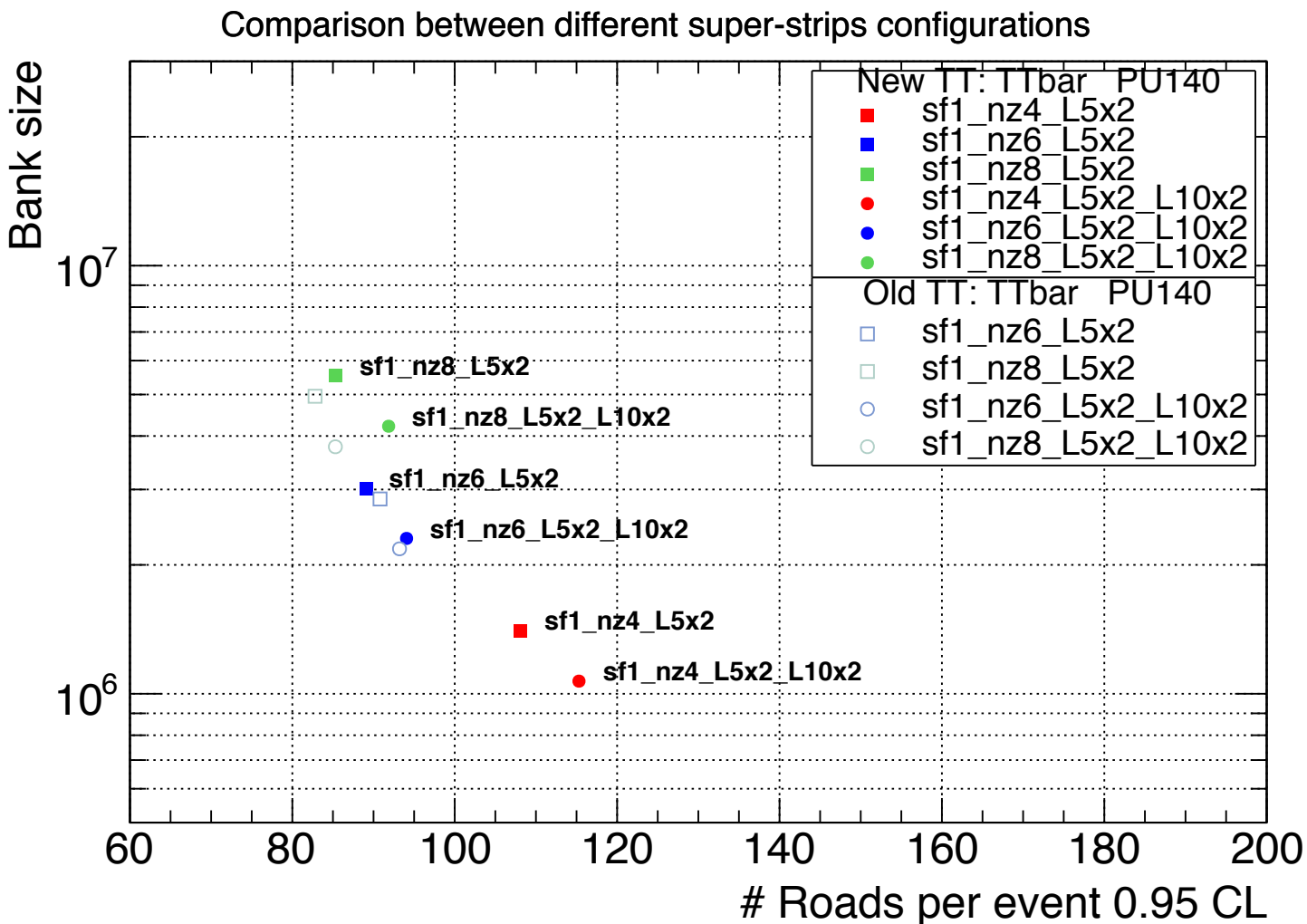
- Pattern bank training sample effective size: $134\text{M} + 66\text{M} = 200\text{M}$ events
- Super-strips defined using full simulation boundaries
- Generated for 6 different configurations:
 - L5x2 or L5x2_L10x2
 - nz: 4, 6, 8

SSConfig	NEW		OLD		Diff
	Bank size 95%	Popularity	Bank size 95%	Bank size 95%	
sf1_nz4_L5x2	1.40E+06	13	1.31E+06		6.8%
sf1_nz6_L5x2	3.02E+06	6	2.85E+06		5.9%
sf1_nz8_L5x2	5.53E+06	3	4.95E+06		11.6%
sf1_nz4_L5x2_L10x2	1.07E+06	18	1.00E+06		6.9%
sf1_nz6_L5x2_L10x2	2.31E+06	9	2.18E+06		5.8%
sf1_nz8_L5x2_L10x2	4.22E+06	5	3.77E+06		11.7%

Popularity

- nz4: Very Good (about 15)
- nz6: Good (more than 5)
- nz8: Fine (more than 3)

Average roads

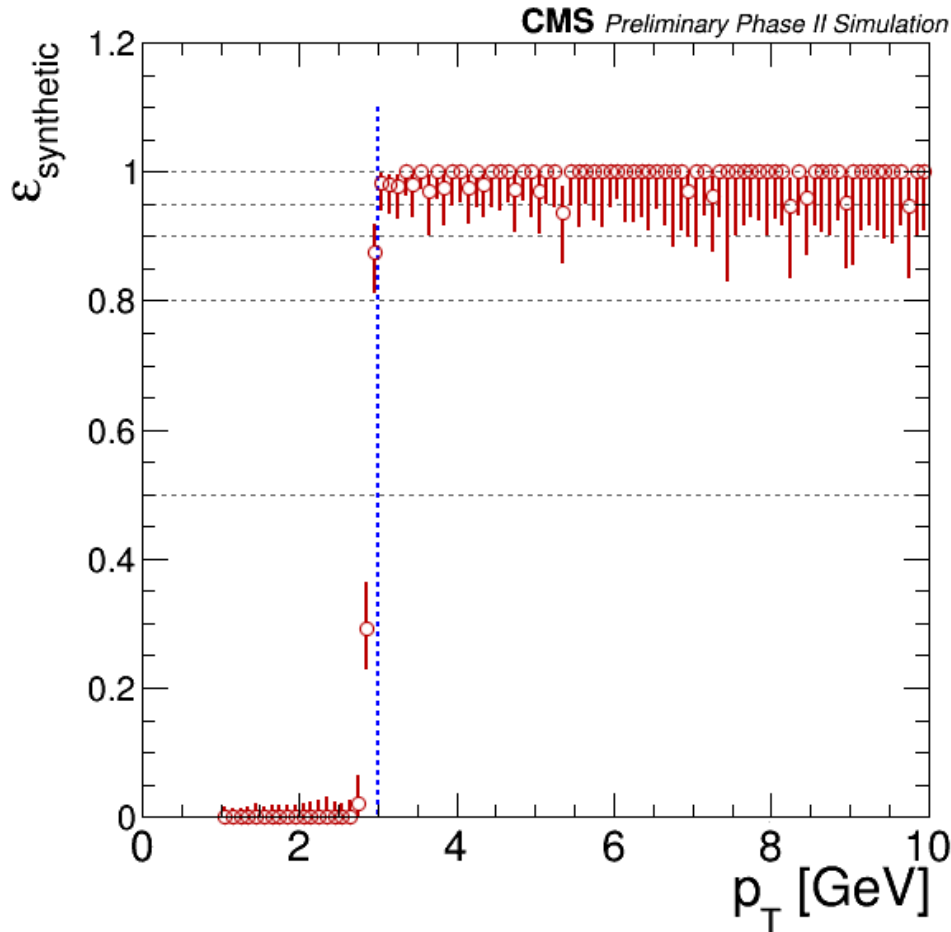


Efficiency performance

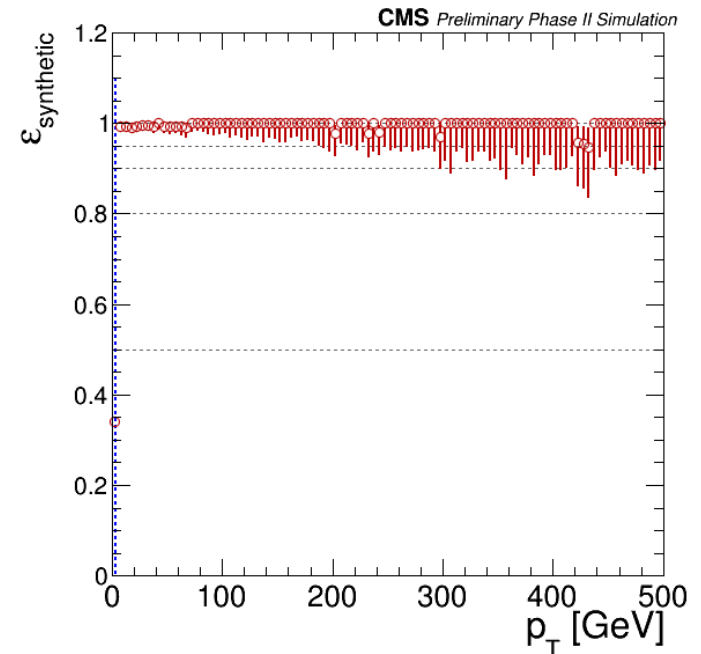
- Goals
 - Test efficiency
 - Effective TT dimensions and turn-on near edges
- Single Muons Test sample
 - Single muons but with delta rays
 - raw 100k events (effective 20k)
- Denominator definition
 - Global: Tracks inside TT phase-space
 - Binned: TT bound removed in the scanned dimension
 - e.g.: scanning $\varepsilon(p_T)$ denominator tracks must be inside TT phase-space in ϕ^* , η^* and v_z , no cut p_T is applied
 - 1 miss allowed: 5 out of 6 efficiency

Efficiency vs P_T

nz4_L5x2



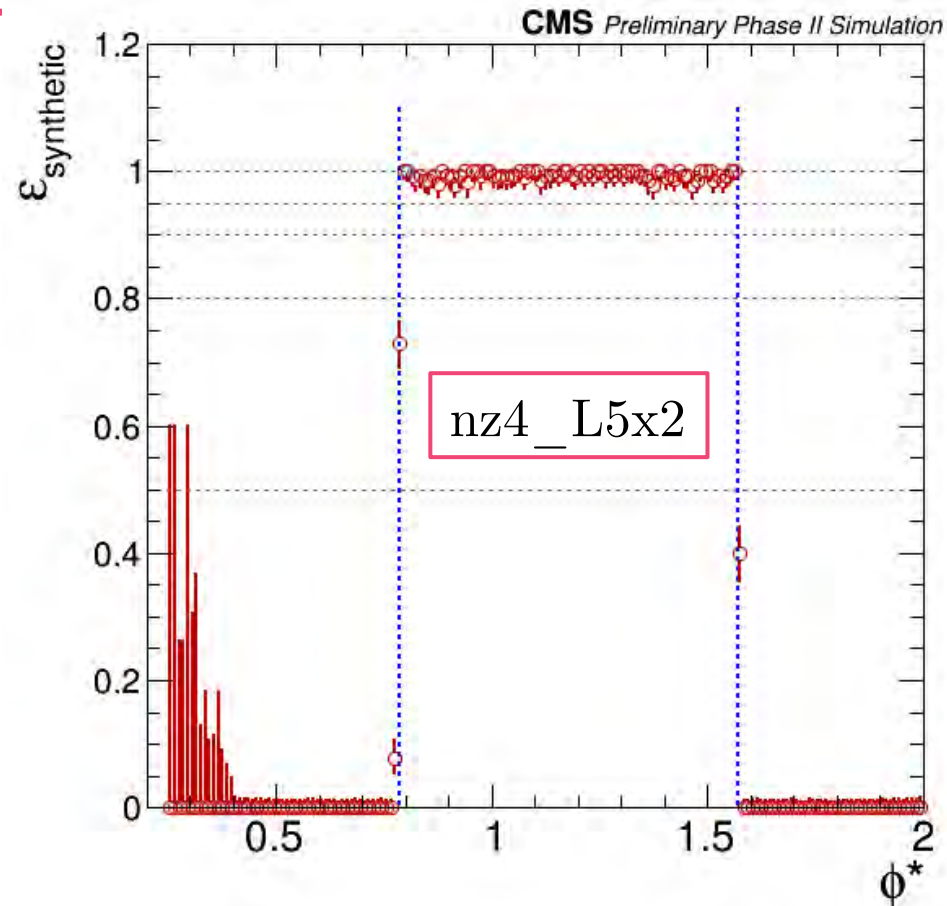
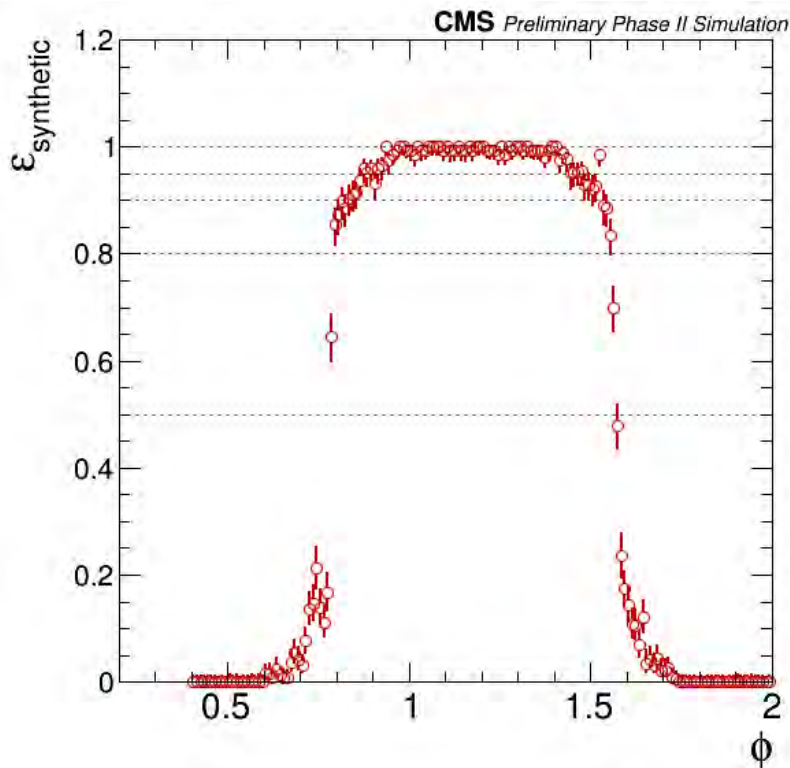
nz4_L5x2



- Sharp turn on
- Average efficiency for $P_T > 3$ GeV 99.2 ± 0.1 %
- No significant differences for nz6 and nz8

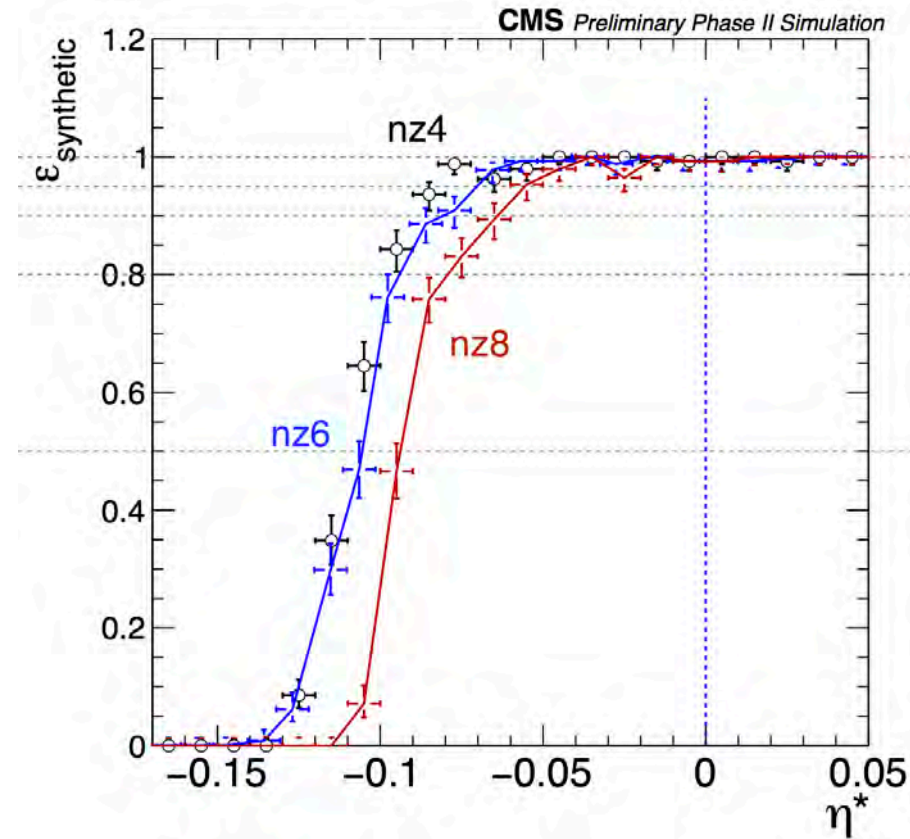
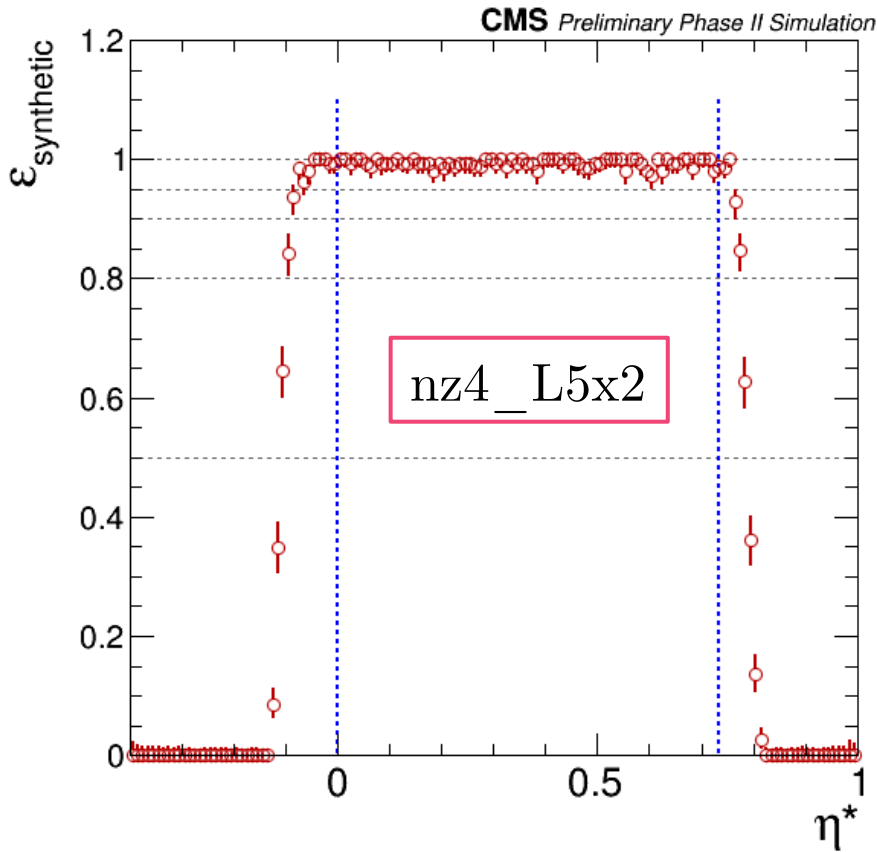
Efficiency vs ϕ^*

- Blind variable ϕ^* (used to define TT)
- nz4 shown (no significant differences for nz6 and nz8)
- ϕ profile in agreement with expectations (see slide 12)



- Very sharp turn on
- Average efficiency inside TT: $99.2 \pm 0.1 \%$
- Null efficiency outside TT borders (no duplicates)

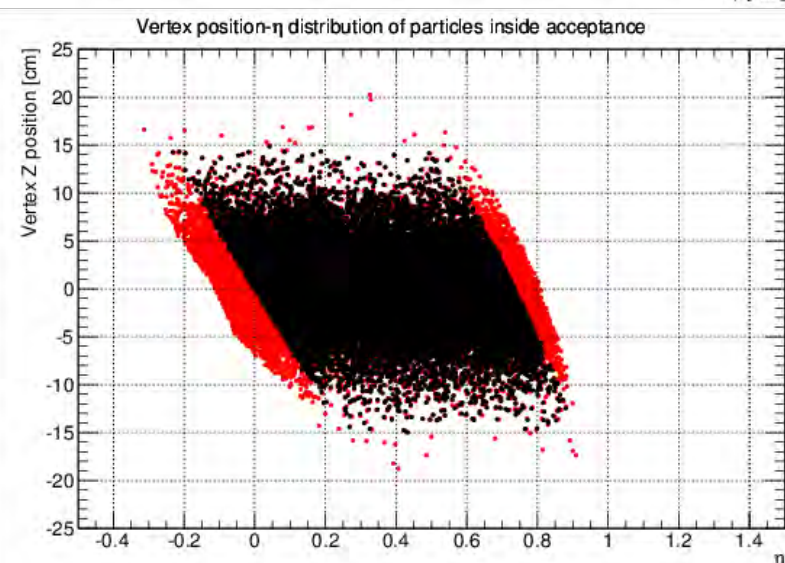
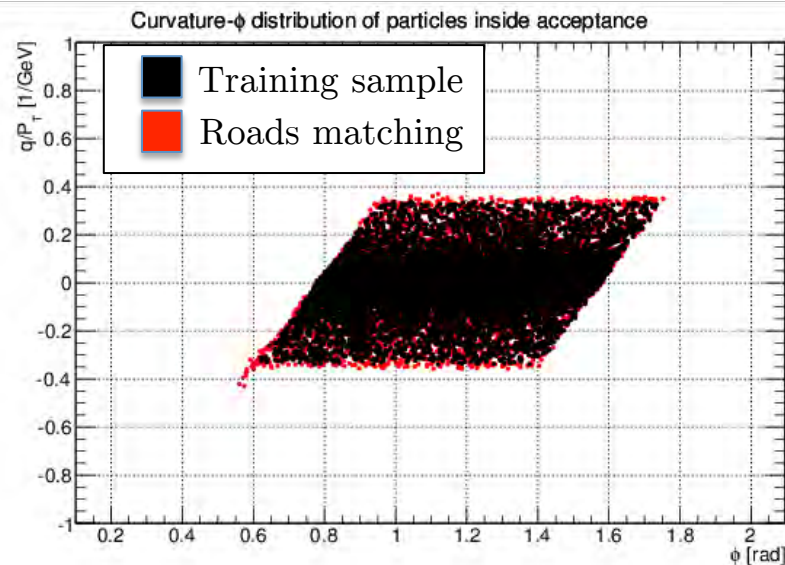
Efficiency vs η^*



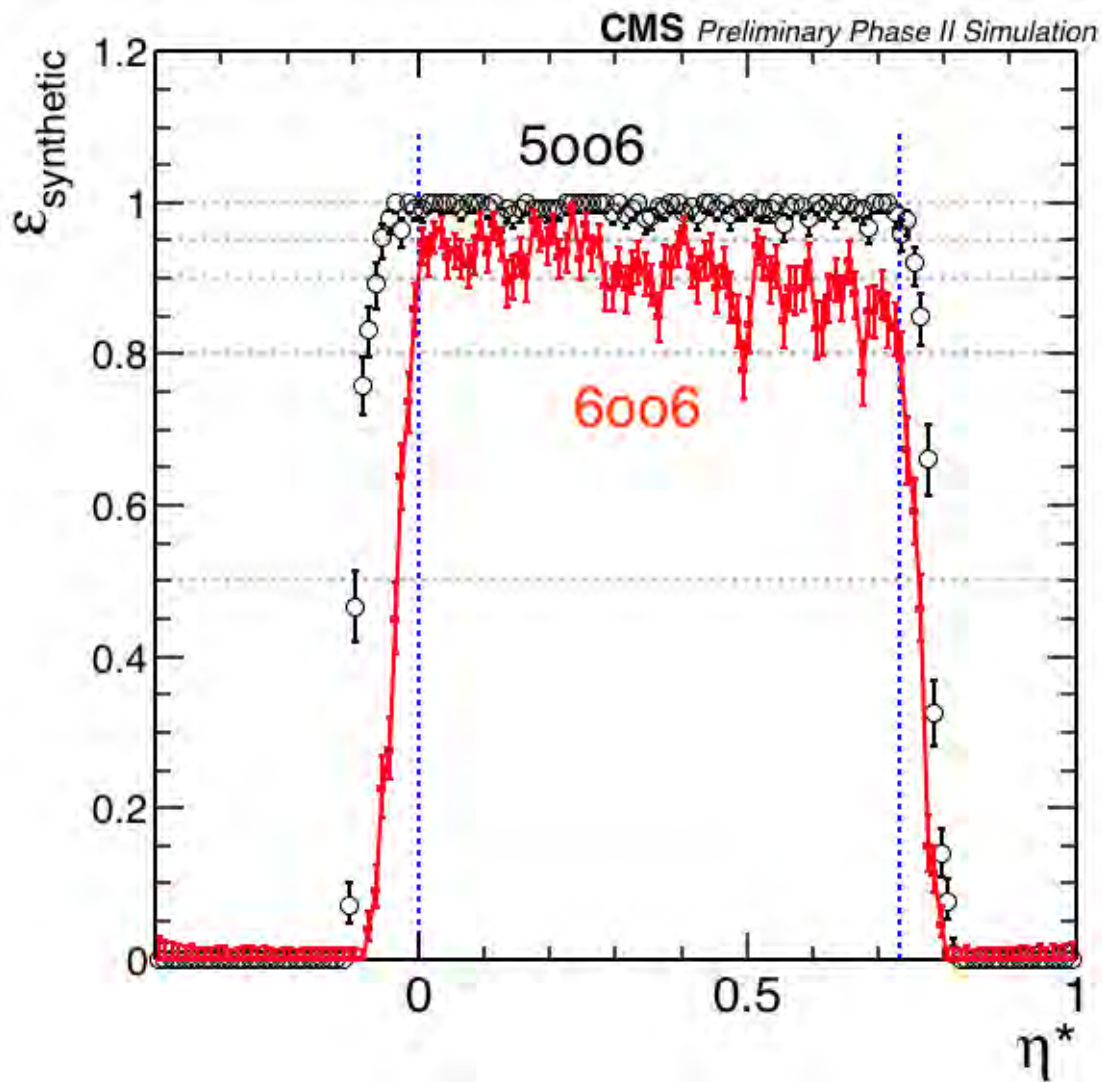
- Early turn on, effective efficiency wider than definition
- Average efficiency inside TT: 99.2 ± 0.1 %
- Turn on dependence from SS configuration

Outside track roads matching

- Particle outside TT definition match roads:
 - Super strips are defined taking the maximum range of interesting particles on TT
 - A single training particle does not lay on the border of every layer
 - Outside particles can do that!!
- Pattern bank acceptance is broader than training sample
- Dependence from SS dimensions
 - Happens in ϕ too but it is far smaller

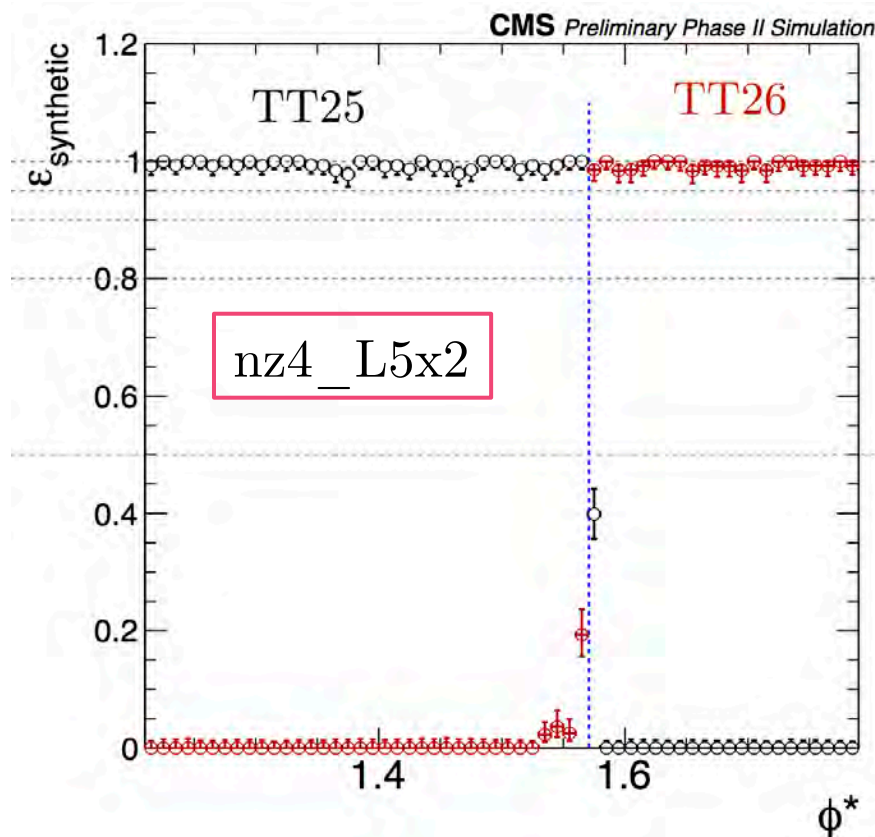


Efficiency vs η^* 6006

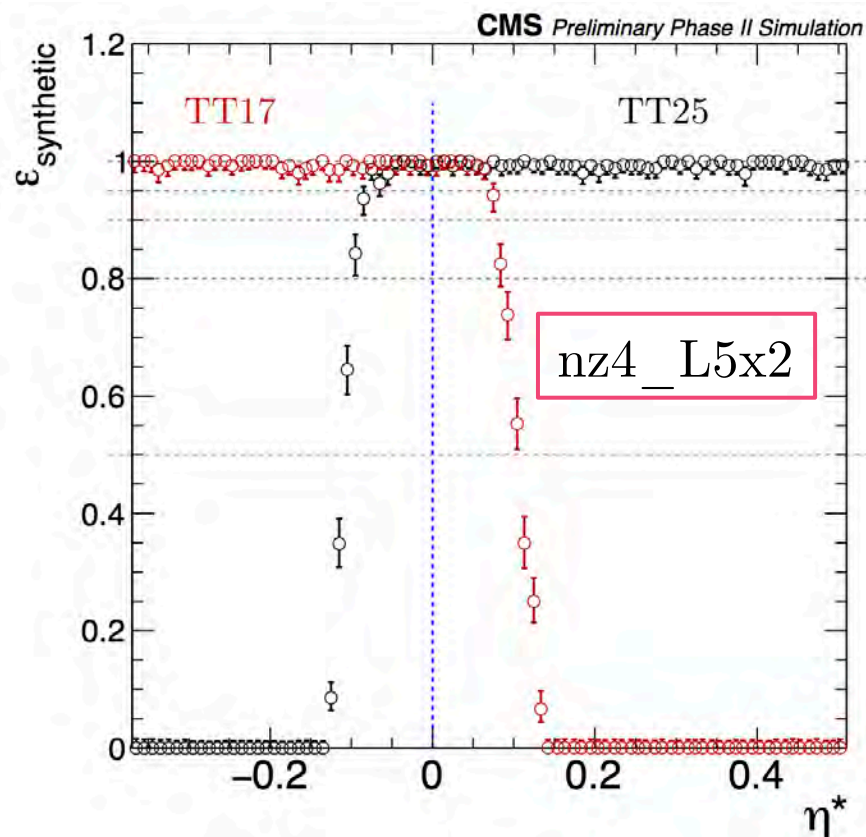


- Sharper turn on w.t.r. to 5006
- Average efficiency inside TT: 90.8 ± 0.3 %
 - PB 95% cut
 - Si efficiency = 1
- Module geometry effect
 - Efficiency drops
 - Slope towards high η

Efficiency near borders



ϕ border :
 TT25 = [4,2]
 TT26 = [4,3]
 TT24 same



η border :
 TT25 = [4,2]
 TT17 = [3,2]
 TT33 in progress

No edge issues!

Conclusions

What has been done:

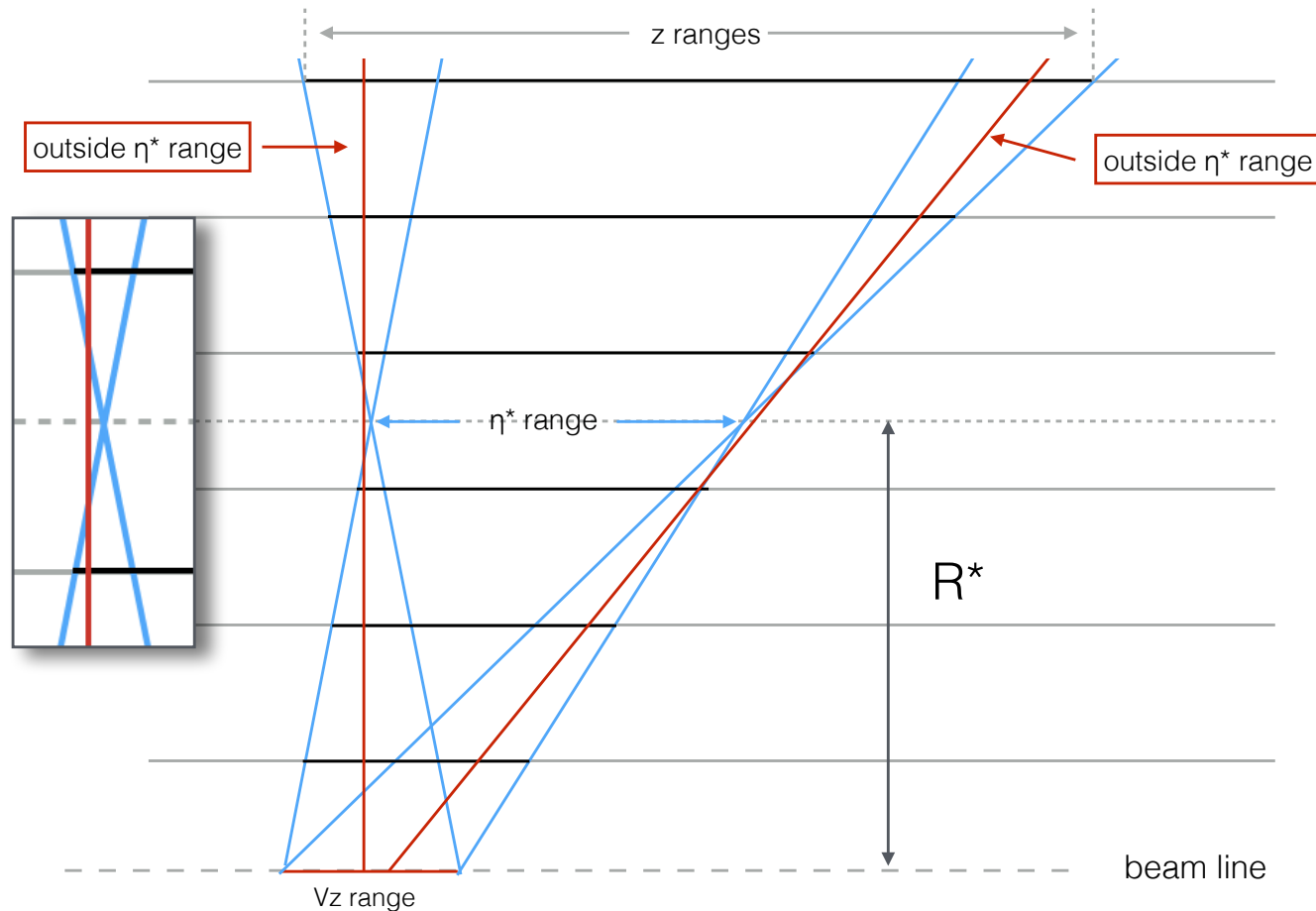
- Study of a new definition of trigger towers
- Optimization of the R^* value
- Efficiency – number of modules trade-off
- Production of new module lists
- Generate AM pattern banks for the new towers
- Make the new towers and the new AM pattern banks available to the full trigger simulation
- Run the full simulation to evaluate new performance parameters
 - Efficiency, Resolutions...

Thank you all!

BACKUP

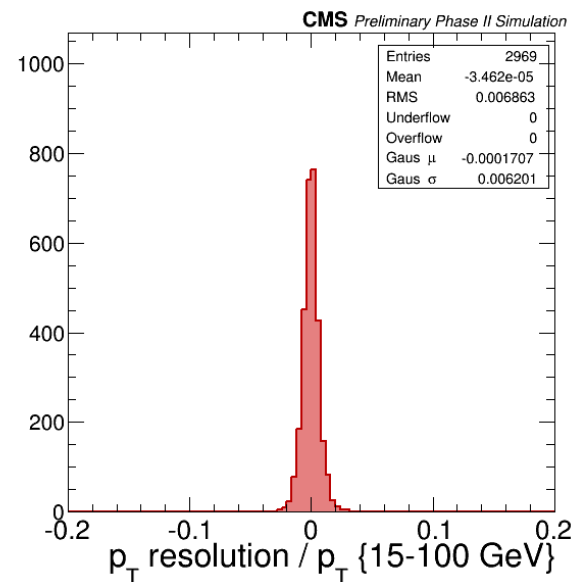
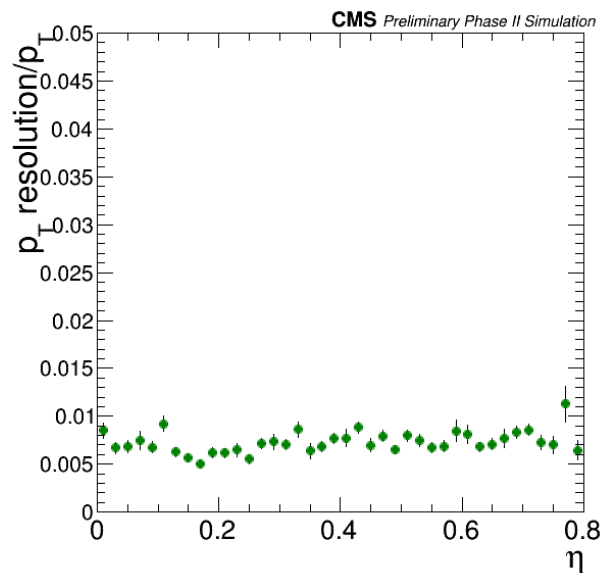
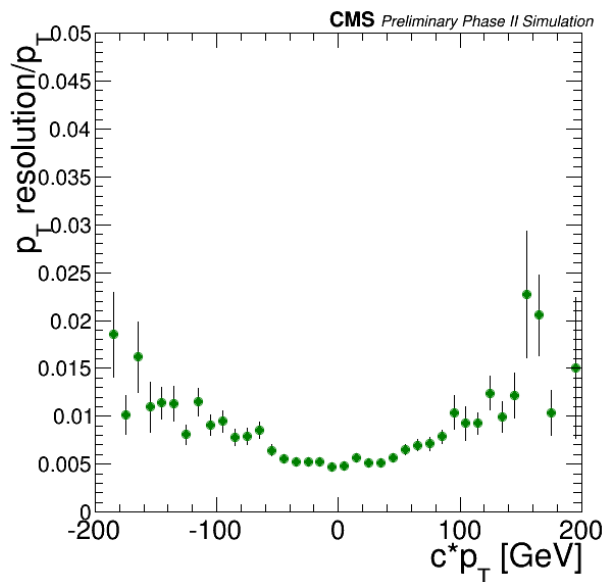
Out TT track example

- Tracks outside TT definitions may match roads if are near border because of SS finite dimensions
- Intrinsic duplicate generation
- Less impact on 6 out of 6



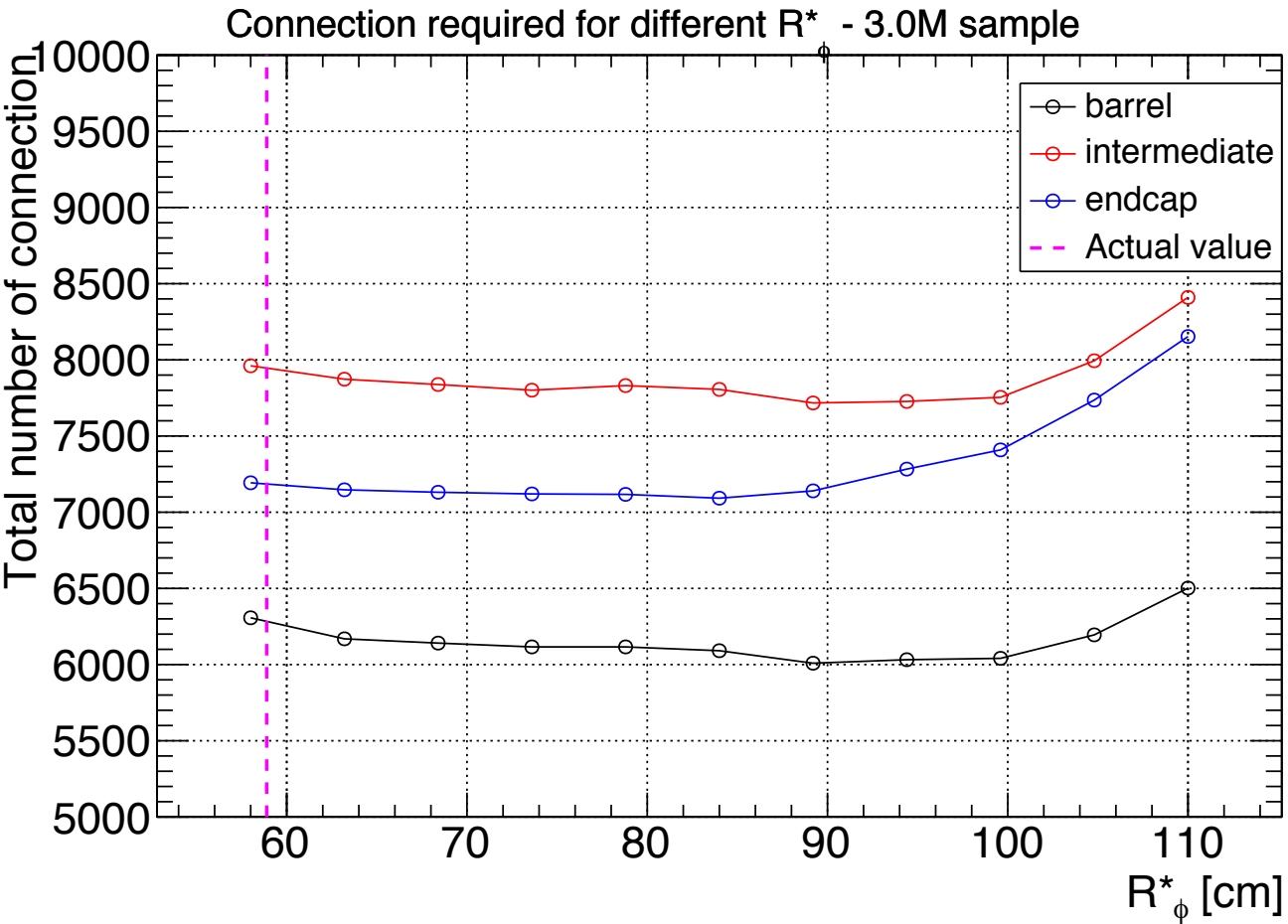
Resolution

nz8_L5x2



Essentially unchanged!

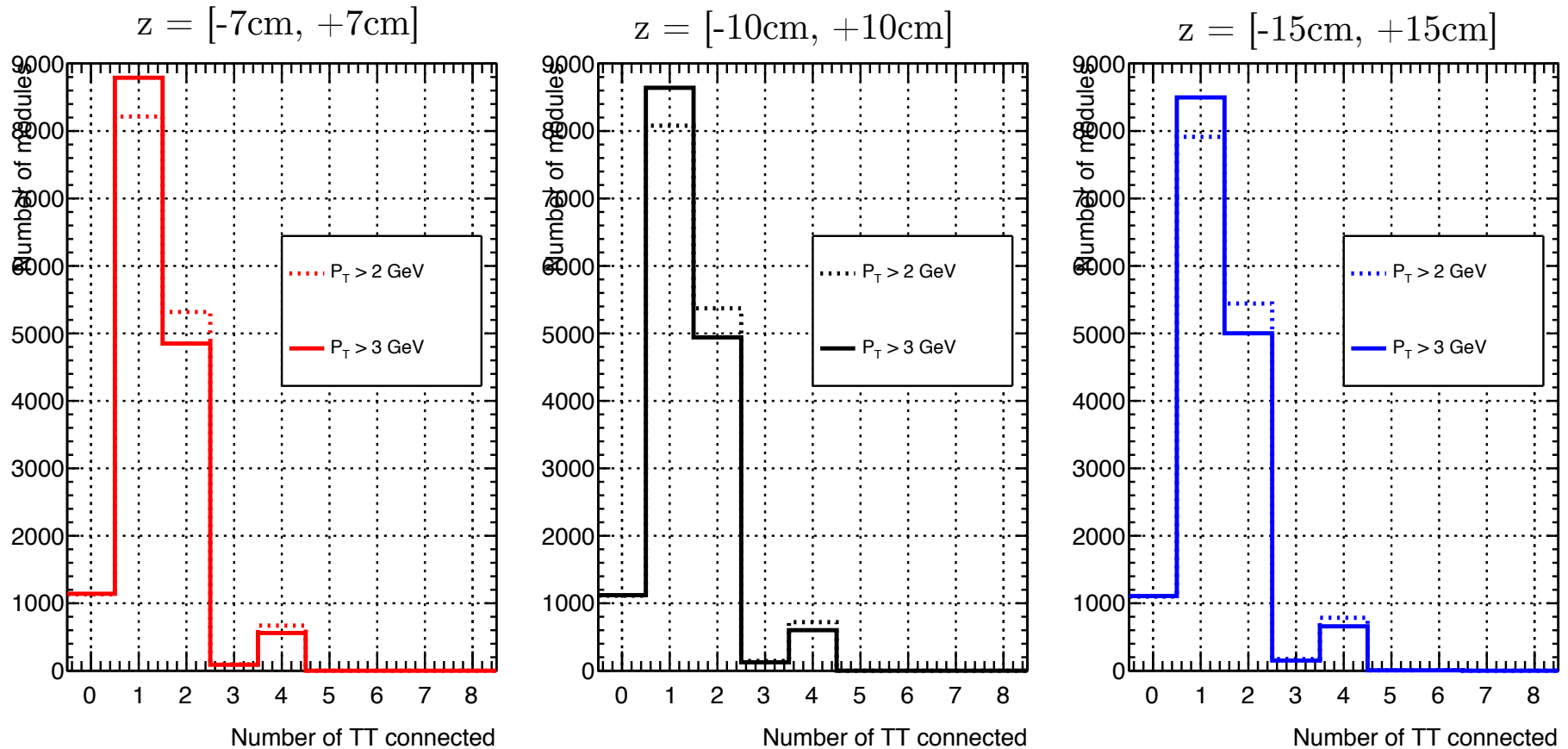
Focusing on R^*_ϕ



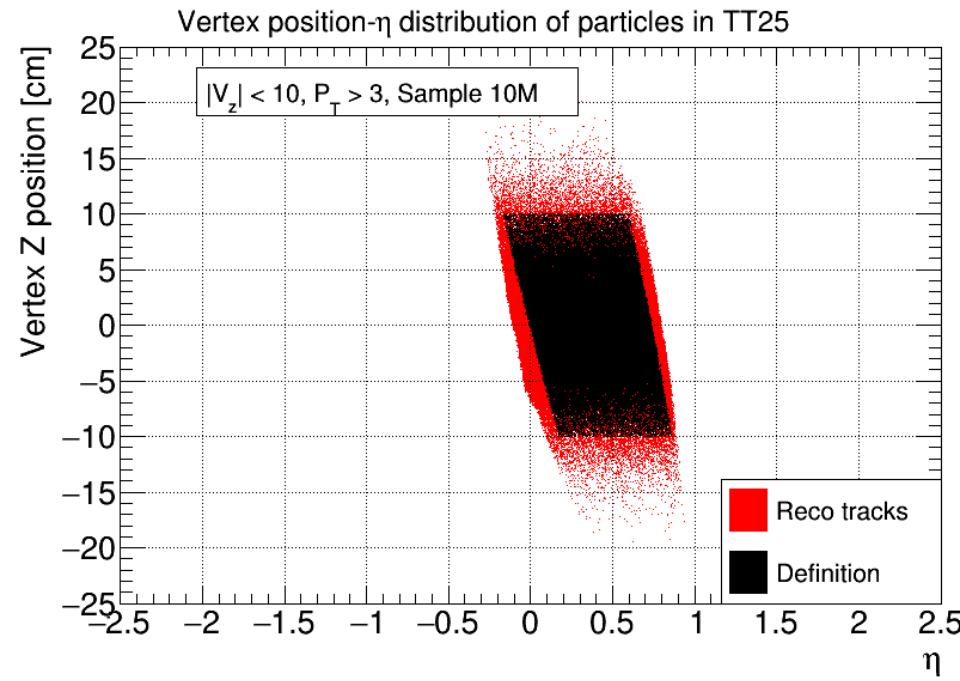
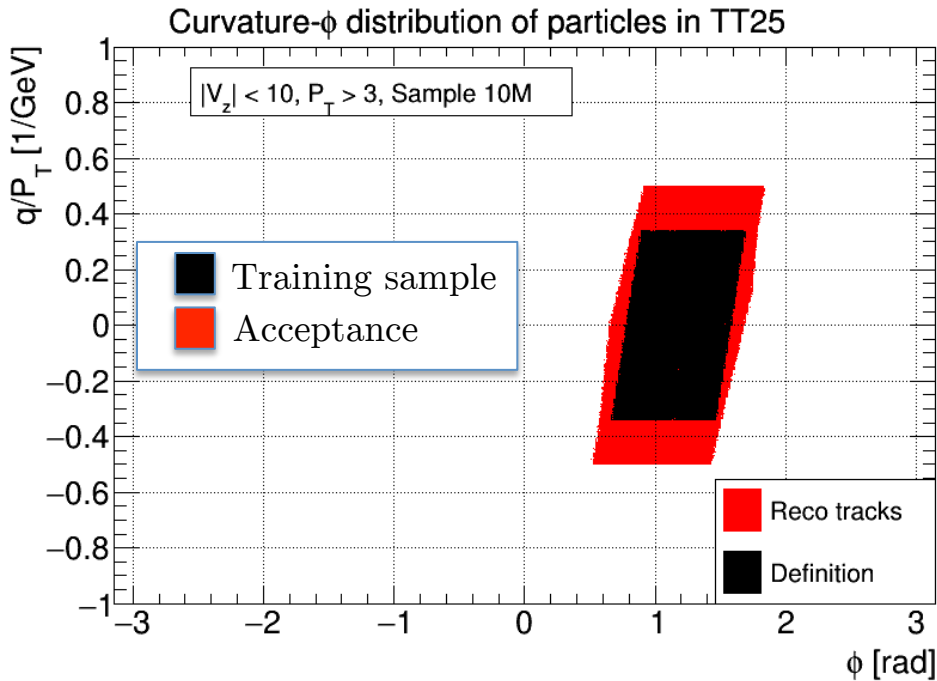
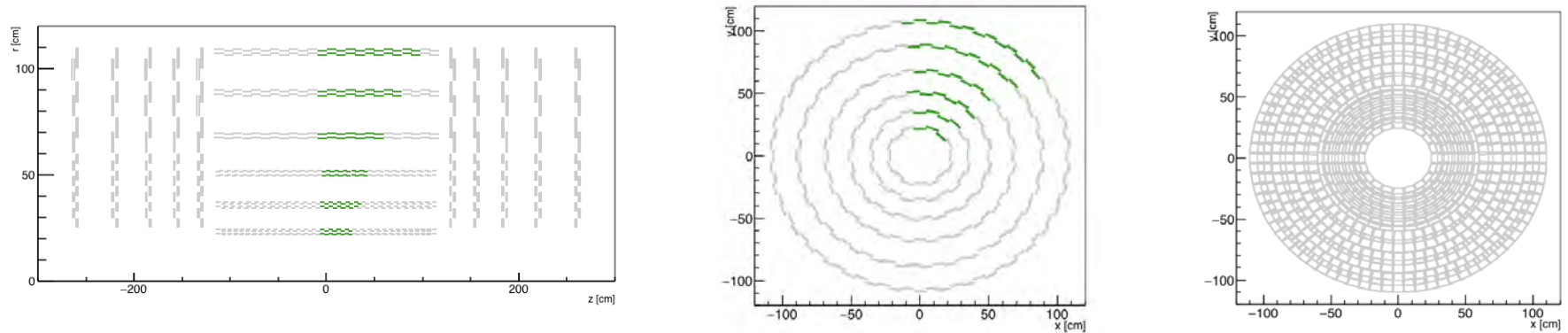
- Max optimization:
 - 4% (intermediate)
 - 1% (forward)
 - 5% (barrel)

Module fan-out

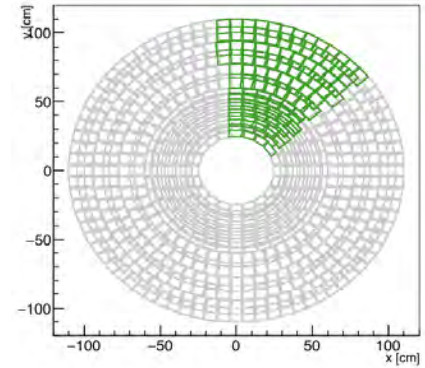
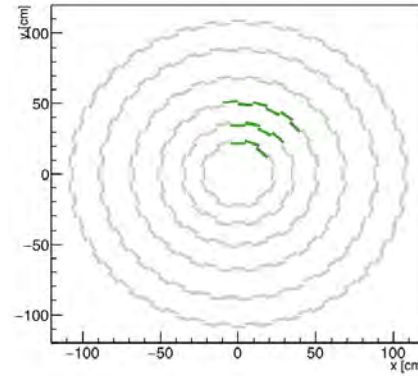
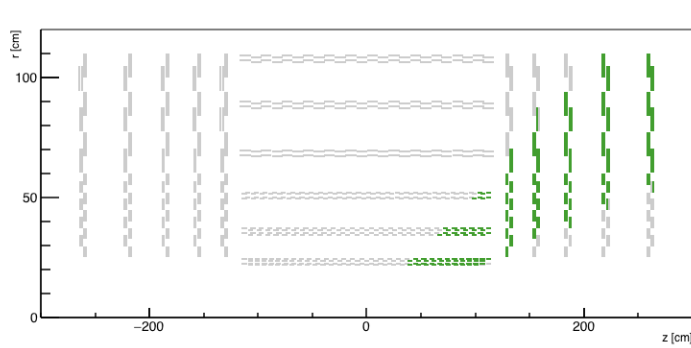
Number of towers to which stubs from a single module must be delivered



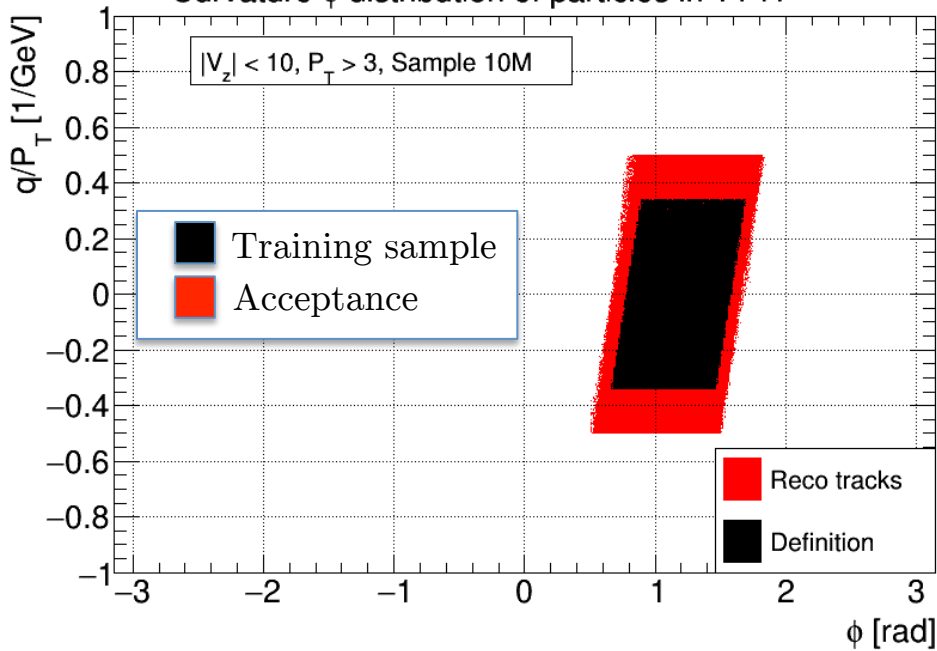
Barrel example – TT[4,2]



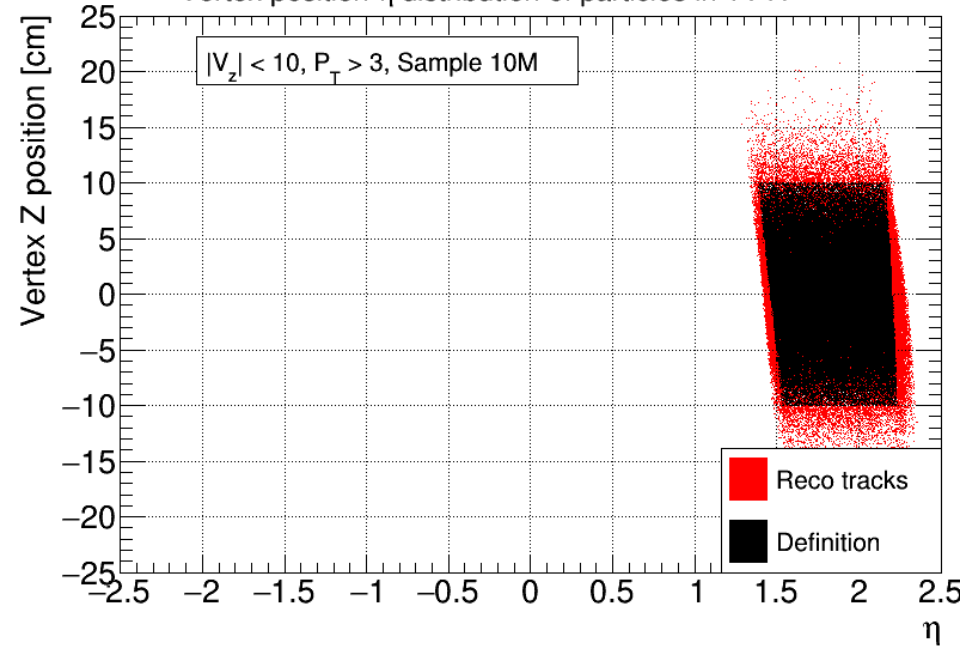
Forward example – TT[6,2]



Curvature- ϕ distribution of particles in TT41



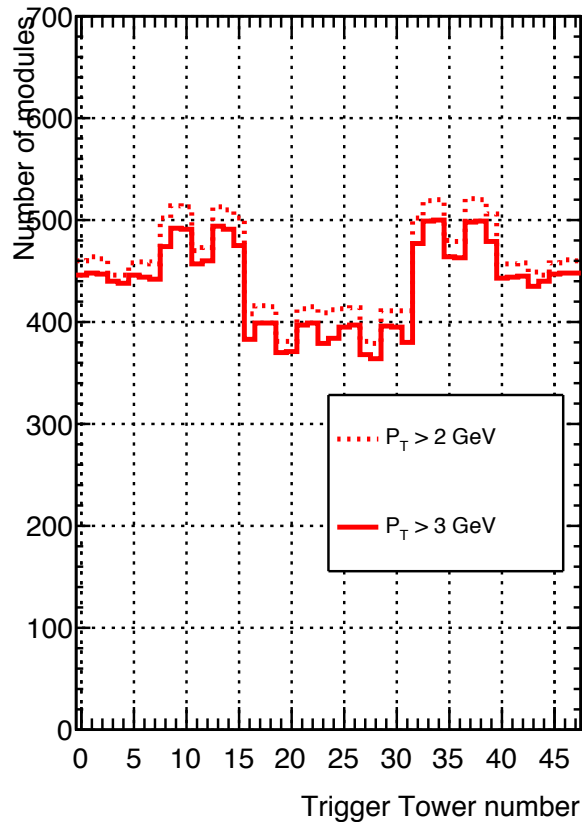
Vertex position- η distribution of particles in TT41



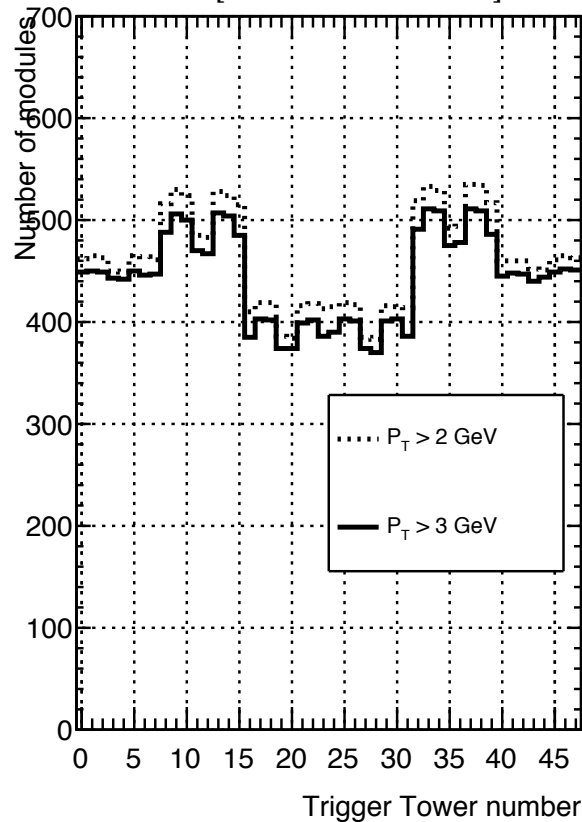
How many modules?

Total number of modules from which each tower must receive information (2GeV vs. 3 GeV)

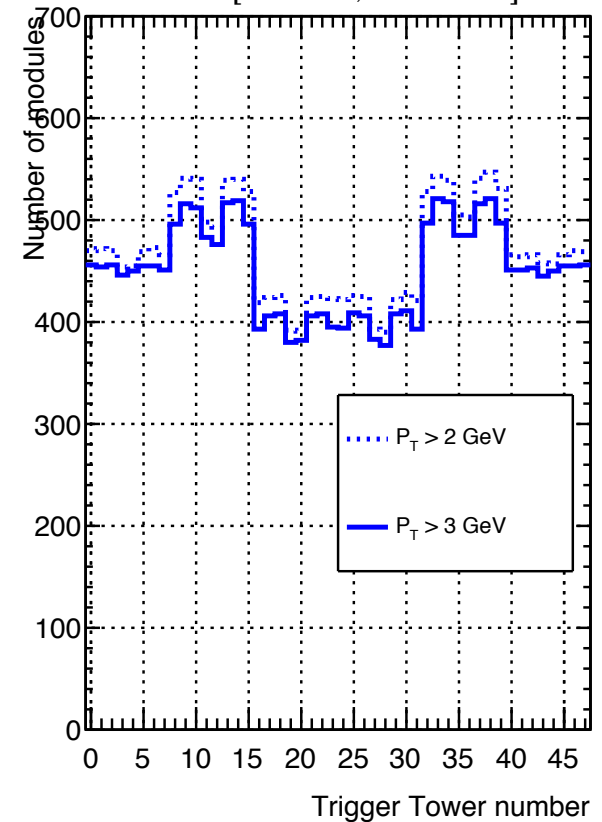
$z = [-7\text{cm}, +7\text{cm}]$



$z = [-10\text{cm}, +10\text{cm}]$

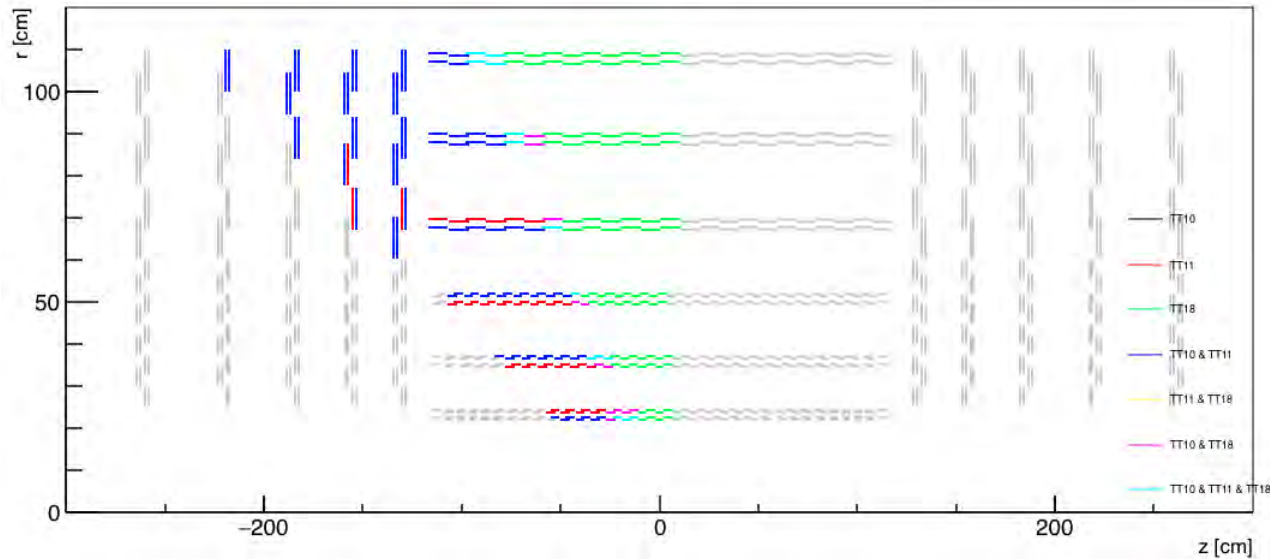


$z = [-15\text{cm}, +15\text{cm}]$

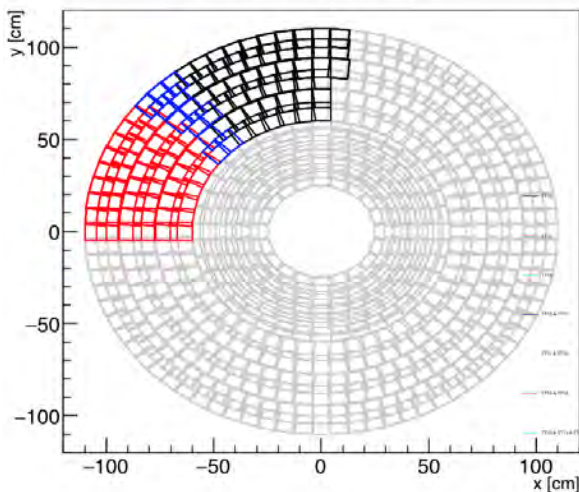


Triple shared modules

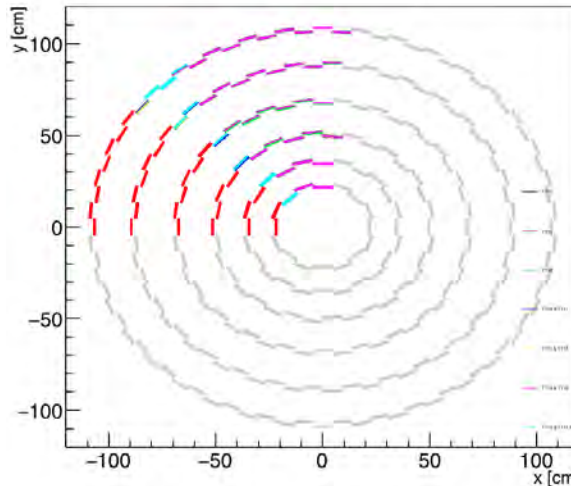
Full r-z projection



Endcap x-y projection



Barrel x-y projection



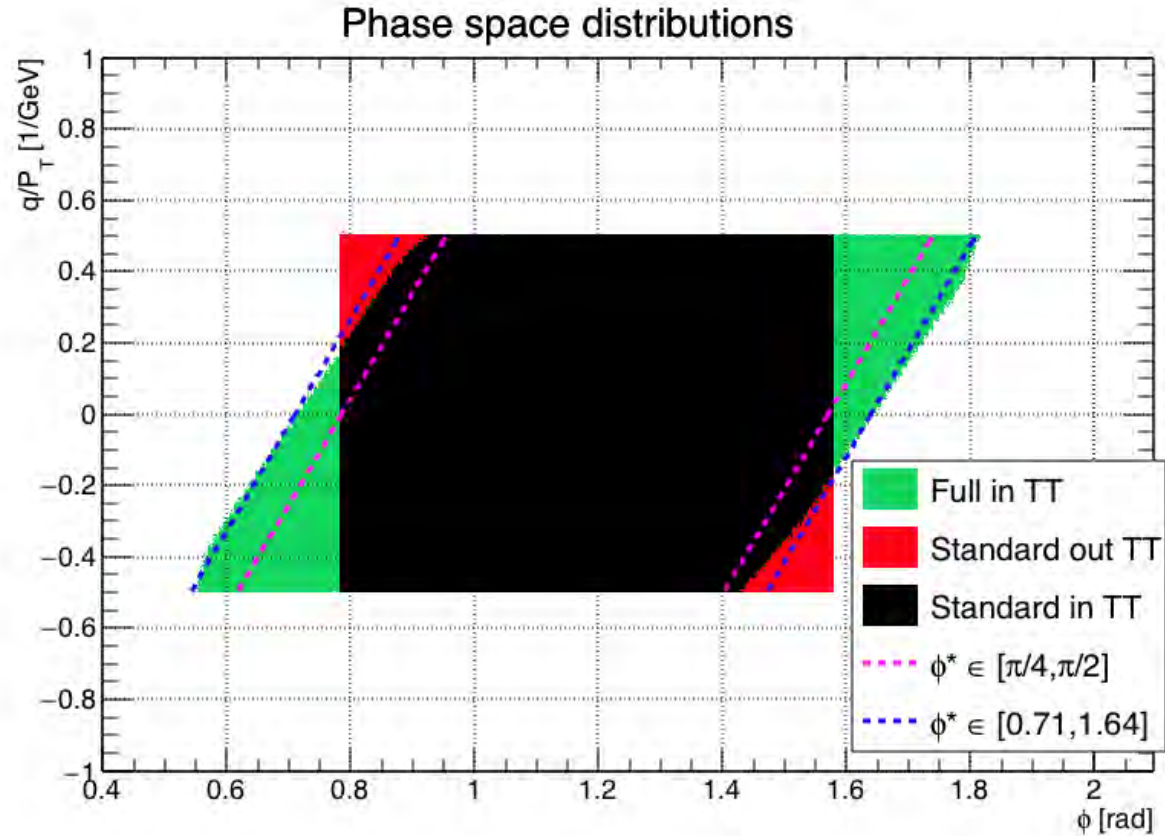
- Less than 1% triple sharing
- Order 4% 4-sharing
- 16 6-time shared modules only with $|v_z|$ up to 15 cm

q/P_T vs ϕ summary plot

Equation of boundary:

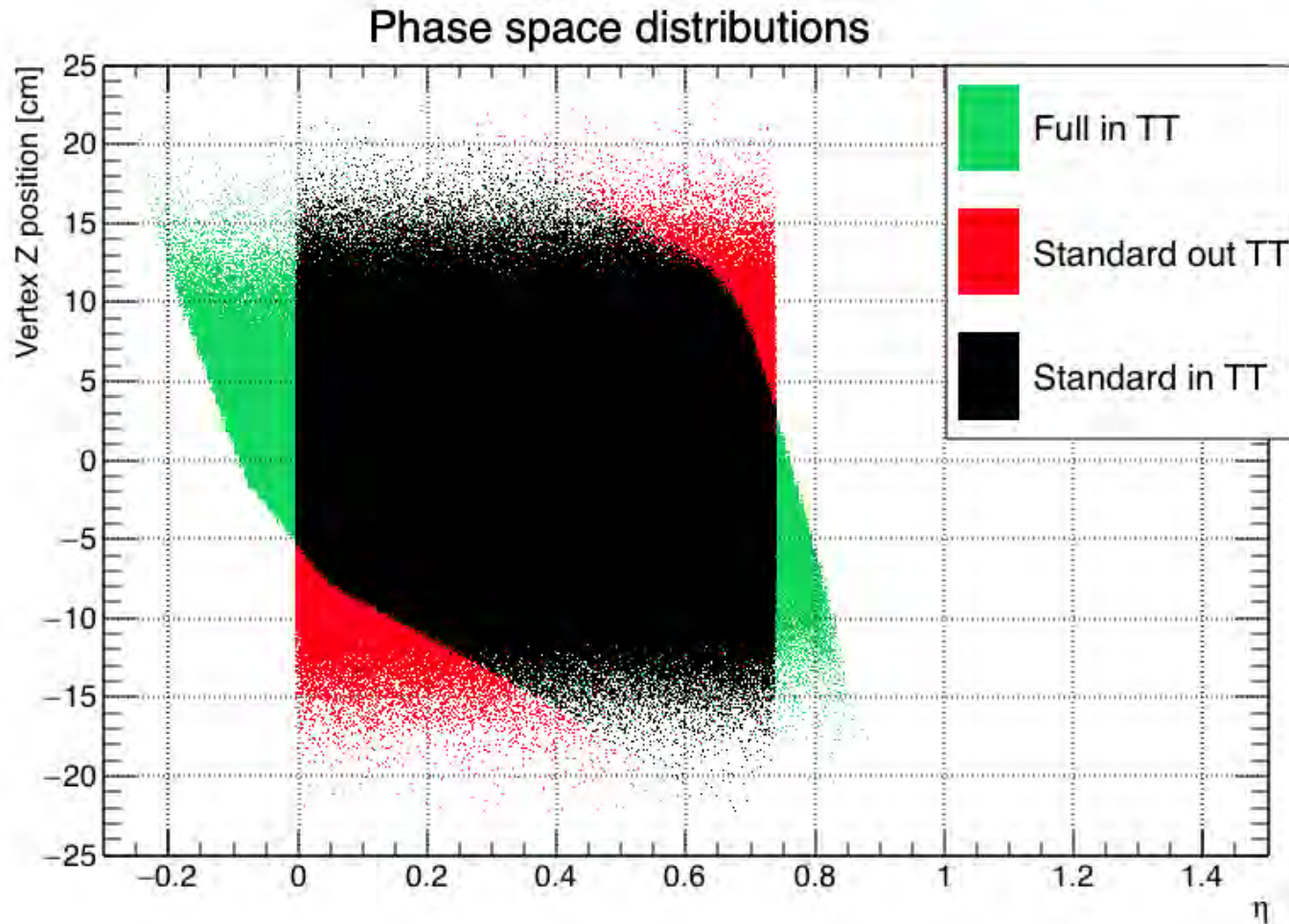
$$\frac{q}{P_T} = \frac{2\alpha}{R^*} \sin(\phi_0 - \phi_{edge}^*)$$

$$R^* = 58.89\text{cm}$$
$$\alpha = \rho/P_T = 87.72\text{cm/GeV}$$



Overcoverage possibly due to finite module dimensions?

z_0 vs. η summary plot



How many modules?

- Dark area: modules directly connected to the TT
- Light area: modules connected to the TT via TT2TT connections
- Solid line: total number of modules connected
- 3 GeV/c P_T

